THE GEOLOGY OF PRINCE CHARLES FORELAND,

AND

ADJACENT PARTS OF NORTH-WESTERN SPITSBERGEN.

A thesis submitted by

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I N D E X .

PART I : INTRODUCTION.

Chapter I.
Brief history of Spitsbergen and Prince Charles Foreland 1.
Present-day conditions 4.
Prince Charles Foreland 6.
Huts. 14.
Weather. 14.
Panoramas.
Previous geological work. 16.
The present work. 36.

PART II : THE HECLA HOEK FORMATION.

Introduction. 41A.

Chapter II. STRATIGRAPHY.

Northern Division.
Fuglehuk group. 45.
Barents group. 50.
Conqueror group. 54.
Scotia group. 59.
Pinkie group. 64.
Larsen group. 66.

Southern Division.
Gordon group. 69.
Geikie group. 71.
Ferrier group. 73.
Isachsen group. 75.
Nelson group. 76.
Kerr group. 77.
Persis group. 79.
Salfjellet group. 80.
Recapitulation. 83.

Basic intrusions. '85.

Chapter III. STRUCTURE.

General discussion. 86.
Upper Structural unit (3) 97.
Unit 4. 100.
Cataclastic effects (unit 4) 103.

Southern range (unit 6) 105.
Effect of Tertiary movements on the Hecla Hoek rocks 111.

Chapter IV. METAMORPHISM

1. The Sediments.

Upper structural unit 116.
Unit 4. 118.
South of Scotiadalen. 122.
Summary 125.

The occurrences of chloritoid. 126.
Summary. 133.

Microphotographs.

2. 2. The Epidiorites.

Effects of regional metamorphism. 134.
Contact metamorphic effects. 140.
Summary. 143.

Problemmatical pyroxenite. 143.

Microphotographs.

Chapter V. THE CALEDONIDES OF SPITSBERGEN. 145.

Work of Kulling. 147.
Work of Sandford. 159.
Ny Friesland - Kulling. 162.
Fleming and Edmunds. 165.
Odell. 172.
West Ny Friesland - Blomstrand. 175
Harland. 175.
The west coast. 176
Prince Charles Foreland. 178.
Conclusions. 180.

Chapter VI. THE CALEDONIDES OF THE NORTH ATLANTIC-ARCTIC PROVINCE. 181.

Bear Island. 182.
Scandinavia. 189.
Great Britain. 213.
Summary. 224.

Greenland. 229.

Conclusions. 252.

PART III : THE TERTIARY ROCKS.

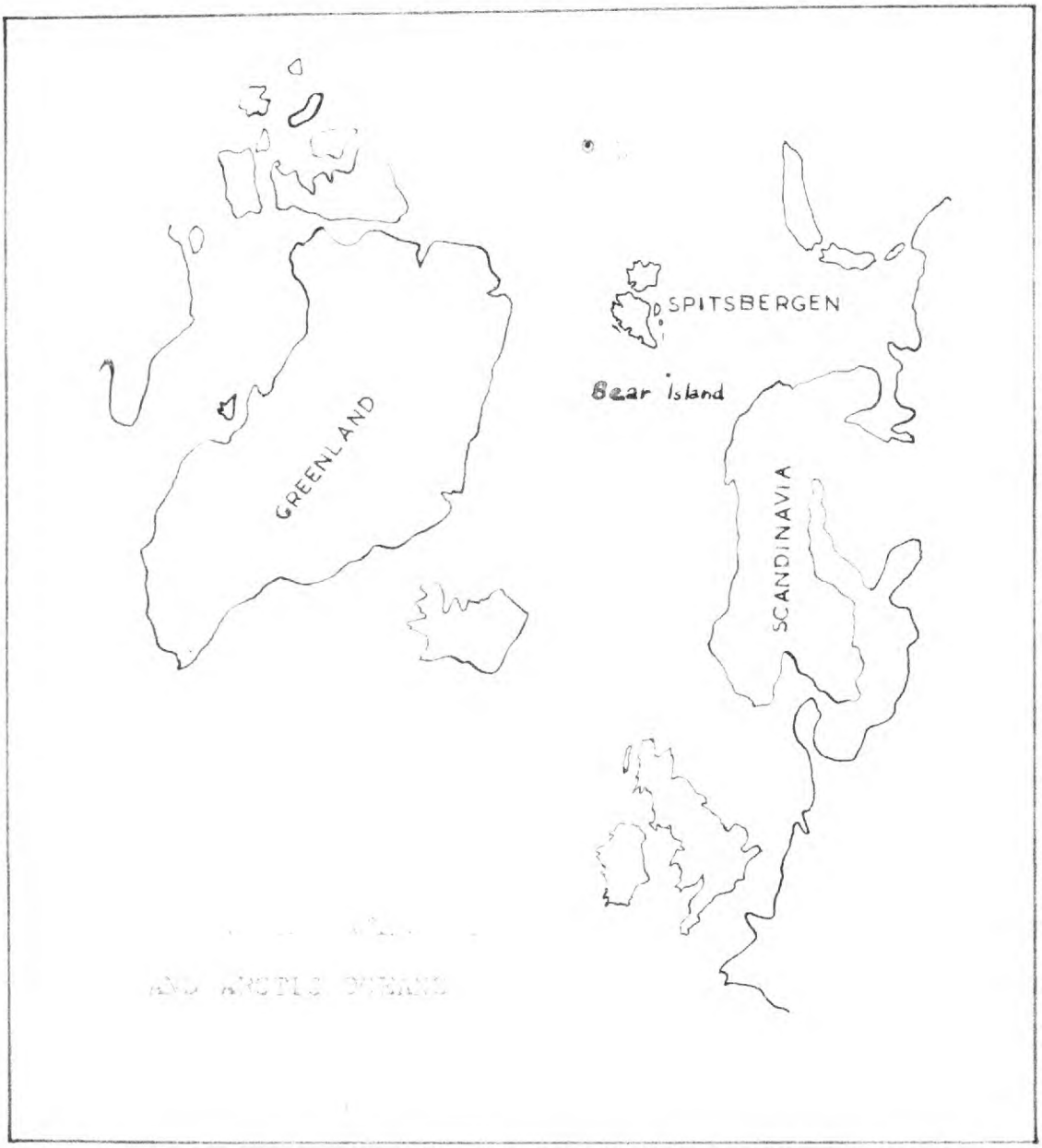
Chapter VII.

Introduction. 258.
Sedimentary Petrology. 259.
Conclusions. 266.
Palaeontology. 268.
Structure. 270.

REFERENCES ..... 272.

PART I

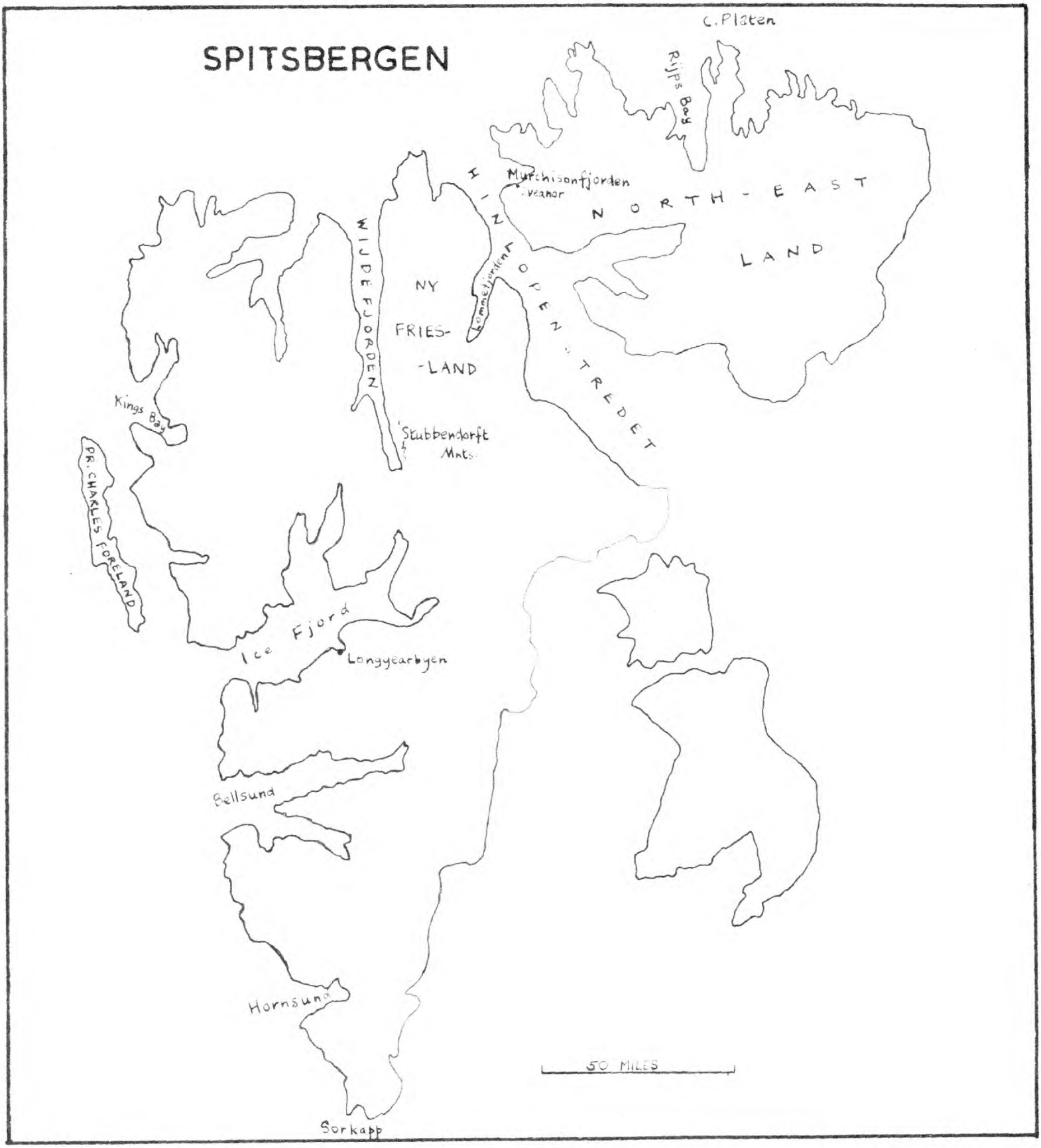
INTRODUCTION.


GREENLAND
SPITSBERGEN
Bear Island
SCANDINAVIA

Brief history of Spitsbergen and Prince Charles Foreland.

Prince Charles Foreland is the most westerly of the large islands of the Spitsbergen archipelago. It lies 765 miles from the N.pole in longitude 11°E. It was first seen in June, 1596, when Spitsbergen was discovered by a Dutch expedition searching for a North-east passage. In the map later produced by the pilot of this party, Willem Barents, Prince Charles Foreland is marked as a peninsula. For its first appearance on the charts as an island it was to wait until 1613.

Soon after the discovery of Spitsbergen, reports that whale, seal and walrus were to be found in large numbers in the coastal waters, resulted in vigorous exploitation by large fleets of whaling ships from England, Holland and other countries. It was in the very early part of this period of Spitsbergen's history that the Foreland got its name, or rather its association with Prince Charles Edward Stewart, later Charles I of Gt.Britain and Ireland. Robert Fotherby in his "Narrative of a Voyage to Spitsbergen in 1613" refers to it as "Prince Charles his Island". The Dutch at this time called it the Isle of Kijn, after a cargo-master who "tried to climb a high hill on the island, fell, and broke his neck". These alternative names vied


SPITSBERGEN
C. Platen
Rijps Bay
Murchisonfjorden
Veamor
NORTH-EAST
LAND
I-Z
NY
FRIES-
-LAND
Lomme fjorden
OLAV TREDET
WIJDE FJORDEN
Kings Bay
Stubbendorft
Mts.
PR. CHARLES FORELAND
Ice Fjord
Longyearbyen
Bellsund
Hornsund
Sorkapp
50 MILES

with one another and a host of rivals ('t Lang Eylandt, t'voer landt, I.Caroli and others) for a hundred years or more, but by the eighteenth century 'Prince Charles Island' or 'Foreland' was more or less established.

The initial activity had by them exhausted itself. The fishery was impoverished and abandoned. All that remained were the ruins of the shore settlements, where the various whaling operations had been carried out, and the scattered crosses that dot the coasts - witness to many grim stories of whale boats wrecked in these waters, and the failure of their crews to survive on shore. In the northernmost 12 miles of the Foreland alone, there are nearly 20 graves.

Spitsbergen was then left alone. For over a hundred years almost the only visitors were Russian trappers. Not until the middle of the nineteenth century did the real work of exploration of the archipelago begin, though some maps had been produced earlier, almost entirely by parties thwarted in attempts to reach the N. pole. It was actually on Parry's 1827 expedition, when an attempt was made to sledge to the pole over the pack ice from the north coast of Spitsbergen, that an anchorage was named 'Hecla Cove' after the expedition vessel H.M.S. 'Hecla'. Nordenskjold later called a mountain SE of the harbour "Hecla Hook" and the name came into general usage for the whole of the pre-Devonian rocks of Spitsbergen : the Hecla Hoek Formation.

Scientific work began about a hundred years ago. Since then expeditions have been made to these regions more or less regularly, from various countries in Europe, more especially Sweden, Norway and Britain. The west coast of Spitsbergen was well known by the latter part of last century, and some tourist boats had even visited Ice Fjord. Nordenskiold had in 1893 sledged across the ice-cap of N.E. Land; but virtually nothing was known of the interior of Spitsbergen when Sir Martin Conway crossed the island from west to east in 1896, with the geologists Garwood and Gregory. In 1897 Conway penetrated into the North-eastern part of the country beyond Billefjorden. Perhaps because of its rather forbidding aspect Prince Charles Foreland was still untouched until, in the three summers of 1906, 1907 and 1909, the Scottish explorer Dr. W.S. Bruce carried out a survey of the island and produced the first detailed map ever published of any large area within the polar regions. Some of Bruce's work, and that of the Norwegian, Gunnar Isachsen, was made with the very considerable backing of H.S.H. The Prince of Monaco, who financed and himself carried out a number of expeditions in his yacht, which resulted in an admirable series of monographs covering a variety of subjects. Perhaps this represents the 'golden age' in Spitsbergen exploration. Royal patronage has now ceased, and it is more difficult for modern expeditions to raise funds.

By the end of the first world war general exploration

was complete : the coast was familiar and the interiors of most of the islands had been traversed and described in a series of narrative accounts. During the last 30 years exploration has therefore been increasingly concentrated on more specialised problems. One no longer has the chance to be the first to visit and explore any major region of Spitsbergen but has to be content with the more intricate work of detailed investigation, and the challenge of the unclimbed peaks.

Present-day Conditions.

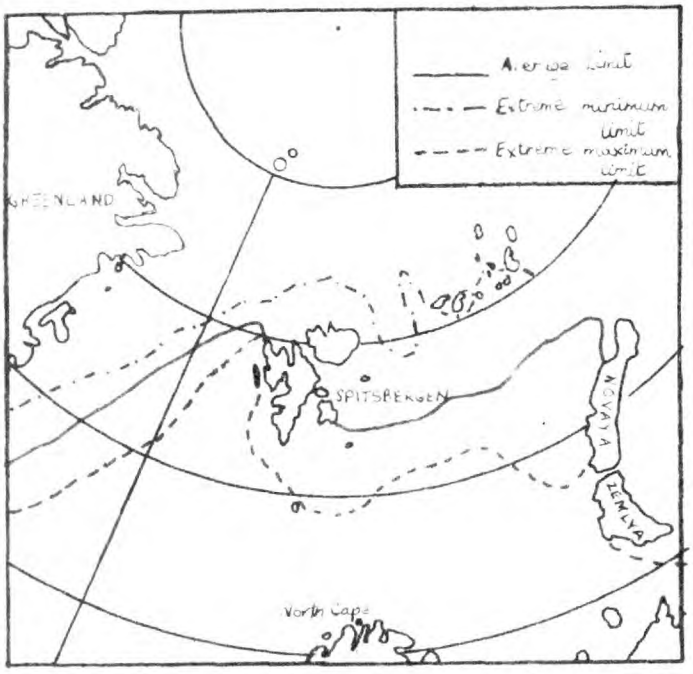
No nation had sovereign rights in Spitsbergen until 1925. Early claims by England, Holland and Denmark were never followed up, and in 1920 a treaty was signed in Paris under which Spitsbergen, Kvitoya, Kong Karls Land, Hopen and Bjornoya (Bear Island) were awarded to Norway whose control began five years later. This Arctic province of Norway, between 74° and 81°N, and between 10° and 35°E, is termed Svalbard and has a total land area of 24,375 square miles, that is about three quarters of the area of Ireland.

The modern economic development of Spitsbergen is a result of the pioneering of several countries during the early part of this century, when for the first time since its discovery 300 years before, coal was mined. At

present only Norwegian and Russian Companies work the coal, though a British Company has recently renewed its mining rights in the region around Billefjorden. In 1953 the Norwegians were working only the two mines at Longyearbyen in Adventfjorden, where the winter population numbers about 1,000. The mines at Ny Alesund (King's Bay) had ceased active production as a result of an explosion during the winter of 1952-3, but about 60 men were keeping the pumps in order and working on general maintenance. Sveagruya - the old Swedish mine at the head of Bellsund - Van Mijenfjorden, which was brought by the Norwegians in 1934, is now abandoned. The Russian mines are at Barentsburg and Grumantbyen on the S. side of Ice Fjord, and at Pyramiden, further NE. at the head of Billefjorden. The Russian population in Spitsbergen is over 6,000, and - though exact figures are not available - coal output is considerably higher than the 400,000 tons shipped annually by the Norwegians. The entire population of Spitsbergen is thus exotic and is centred closely around the half dozen mines.

Shipping is impossible during the winter months November to April. The sun is continuously obscured for 4½ months, and even if breaks in the pack ice occur, the sea temperature is so low that water washing over the decks quickly freezes up the scuppers and unless hacked away and thrown overboard soon capsizes the boat. Even as far south as the Arctic

Diagram 3.



ICE LIMITS IN THE MONTH OF AUGUST

fishing grounds of Norway, this difficulty is common in the winter. However, from May to October the west coast is usually at least partly free of ice (see diagram 3) and at the height of the summer a regular service of Norwegian colliers takes the coal mined at Adventfjorden during the winter to various ports in Norway and the Baltic. Apart from these boats, which only carry passengers under special arrangement, the only means of access to Spitsbergen is by specially chartered boat, or the small Tromso steamer 'Lyngen' which since 1951 has been taking tourists to Longyearbyen, Kingsbay, Magdalenefjorden and back to Tromso in ten day trips during part of July and August. There is of course no kind of organised transport from the mining areas to the uninhabited Prince Charles Foreland.

Prince Charles Foreland. (See map G).

The island is 54 miles long, varies from 3 to 7 miles in width, and has a total area of just over two hundred and fifty square miles. It lies between 78° 54' and 78° 12' N; and 10° 30' and 12° 10' E. It is elongated in a north-north-westerly direction, parallel to the west coast of the largest island of the Spitsbergen group (namely Vest Spitsbergen) from which it is separated by a sound from 3 to 10 miles across. At its shallowest point off Murraypynten the depth of Foreland Sound (Forlandsundet) is only 3 fathoms.



Plate 1. Fuglehukfjellet from N.W.

The coasts of Prince Charles Foreland are for the most part nearly straight,,with few deep indentations. The west coast in particular is very rocky and abounds with reefs - in some areas for as much as two miles from the shore.

In form, the island is constituted of two simple elements - the backbone mountain range, and the flat low raised beaches which fringe it (see for example plates 5 and 7)

The mountains fall naturally into groups, their features varying according to the dominant rock types. At the north tip of the island (plate I) the rocks rise sharply in a most impressive wall to a height of nearly2,000ft. The precipitous cliffs of massive quartzite are an ideal nesting place for the seabirds, and in summer in this neighbourhood the polyphonic squawks of gulls, guillemots, puffins and auks are deafening. This composite mountain mass three miles long, is Fuglehukfjellet, (plate IIa) the "mountain of the Bird Hook" - (the Norwegian suffix "fjell" being equivalent to "Mount").

To the south the mountains are higher, but smoother in outline, with slates and thin limestones as the predominatingrock type (plates IIa & IIb). Barentsfjellet, is followed by Balfourfjellet, and then the two mountains of the Sutor group. The eastern parts of these are of the same soft, scree-covered form as the mountains just to the N., and are called Stairhogdene, and St.Andreashaugane (north and



Plate 2. Central range from Boureefjellet.

south respectively). At the western ends of these mountains are two jagged pyramids of bare rock, both about 1,200ft. high, towering up from a rocky promontory, forming one of the best known landmarks of the Foreland - the Nordre and Sore Sutorfjella. Two small and innocuous hills, Leefjellet and Hellandfjellet form the southern part of this undramatic group, which covers the northern 13 miles of the island.

Abruptly, to the south, the scenery changes as the massive quartzites of Fuglehuksen reappear (plates 2 & 13). Laurontzonfjellet and Boureefjellet lead to the great range of peaks which occupy the central 8 miles of the island. Scoresby, in expansive mood, describes them thus :- "The points formed by two or three of them are so fine, that the imagination is at a loss to conceive of a place, on which an adventurer, attempting the hazardous exploit of climbing one of the summits, might rest. Were such an undertaking practicable, it is evident that it could not be effected without imminent danger. Besides extraordinary courage and strength requisite in the adventurer, such an attempt would need the utmost powers of exertion, as well as the most irresistible perseverance." From the plain on the west and the piedmont glacier on the east, the mountains rise as a jagged backbone to nearly 4,000ft. above sea level: for 6½ miles the ridge line never falls below 2,000ft. Only two glaciers reach the western plain, but on the east side of the range the high snowfields feed a series of icefalls



Plate 3. 1000 ft. ice fall east of Monacofjellet.



Plate 4. West face of Jessiefjellet.

and glaciers which coalesce at the foot of the mountains to form Buchananisen - a seaward sloping strip of ice eight miles long, and generally between one and two miles in width (plates 3, 13 & 19). The sea has broken through the moraines and cut back into the ice so that over most of its length the glacier is terminated by ice-cliffs, reaching a height of 100ft. in places.

At the north end of this central range are the three peaks of Rudmosefjellet, with the ridge of Veslefingeren to the east (plate 13). The Grampianfjells follow to the south with first Monacofjellet -(the highest and most beautiful of the Foreland mountains - 3,640ft.)- and then Phippsfjellet with eastern prolongations to Djevletumen (the "Devil's Thumb") and Buchananryggen ("the Nunatak".) The 'Thumb' is an immense rock tower 2,700ft. high bounded by very steep crags on the east and south-east sides, with a vertical NW face falling 1,600ft. to the ice below: on the SW side it is joined to the main mass of Phippsfjellet by a narrow snow col. Parnassfjellet follows, then Charlesfjellet and finally the slender pyramid of Jessiefjelliet, its height less than a 100ft. short of Monacofjellet. (Plate 4).

The general level of the mountains then falls to about 2,000ft. or a little less (plate 14a). Margaretfjellet sends out a spur (Krokodillen) eastward, against which the southern half of the Buchananisen ends. A ridge from



Plate 5. View north from Ferrierpiggen.
Selvagen and Sesshogda in the
middle distance.

Geddecfjellet runs to the junction of the north- and eastward extending arms of Alfred Larsentoppen, and in the two bowls so formed lie Magdabreen and Alfredbreen (breen= glacier). The long ridge south of Magdabreen is called Sesshogda.

The most important embayment of the E.coast - Selvagen) is situated to the south of Alfred Larsentoppen (plate 5). From the head of the bay, the valley of 'Scotia Glen' (Scotiadalen) runs across the island in a S.S.Westerly direction to Haukebukta on the west coast. The watershed lies at only 240ft. above sea level.

To the west of 'Scotia Glen' the main range is continued for six miles by a series of hills averaging 1,800ft. in height. Conquerorfjellet to the north is followed by a small hill we have called 'Backbiter', and then by Scotiafjellet and Ormondryggen - a ridge 3½ miles long. The S.W. end is composed of massive quartzites, which make the forked peak Tvihyrningen; the N.E. end is lower, and rounded.

To the east of this group, on the other side of Scotiadalen begins the 'southern range' (plates 6 & 7), a wedge shaped massif which extends about nine miles from the south shore of Selvagen to Methuenfjellet. The mountains are mostly about 2,000ft. high, (Hardiefjellet, 2,450ft., is the highest) and are less jagged in character than those of the central range. On the east side of the range are three



Plate 6. Southern range from the hut at Kenmore. Hannayfjellet covers the whole of the centre of the picture; Hardiefjellet in the distance.

large glaciers, which almost reach the sea, the northern one James Geikiebreen; the southern two formerly coalesced and were called Archibald Geikiebreen. Smaller glaciers also occur in the eastern corries of Ferrierpiggen and Methuenfjellet. On the northern side of the range are a series of five glaciers (none of them yet named officially) moving northward, and on the west side three glacier relics coming from the N.W. corrie of Hannayfj. and the N.W. and S.W. corries of Hardiefjellet. The range begins south of Selvagen with the massif of Doddsfjellet, the largest single mountain system in the island. The actual peak called Doddsfj. is in the centre, 2.094ft. high, but two of the peaks of the mountain further S.W., which we have called 'Laurel' are in fact higher, being over 2,200ft. (see Map G.) Doddsfj. sends out a great N.E. arm to Ferrierpiggen (1,650ft.) and another to the N: between these lies a large glacier. The long N.W. ridge of Laurel, extends to Alasdairhornet, and a third glacier lies N.E. of the ridge.

The col to the south of this massif is just below 1,000ft. and leads to the long E-W ridge of Hannayfjellet, with its curling eastern spur. The lowest pass of the southern range (MacRitchieskardet, less than 800ft.) separates this from the mountain mass to the south. There are three prominent peaks, the northern one (just over 2,400ft.) highest - Johansenfjellet: the central one Neukpiggen, and the southern Isachsenfjellet. The ridge which runs S.E. from



Plate 7. Air photograph of the southern range.
Southern tip of the island in the far distance.

Johansenfjellet and divides the two parts of Arch.Geiklebreen, is "Dumbell Ridge".

The highest peak of the range, Hardiefjellet, follows, after a 900ft. col, and is joined by a high ridge to 'Nelson': the latter sends out a prominent ridge to a conical hill of 1,300ft. Methuenfjellet forms the southern, sharp end of the wedge.

In general the slopes on the east side of the range are much less than on the west, where huge slabs tilt away from the summit ridges at about 50° or 60°, down to the raised beach plain (plate 7). The slabs are bedding planes of massive calcareous schists, and large parts of a mountain side may be sculptured from a single bed.

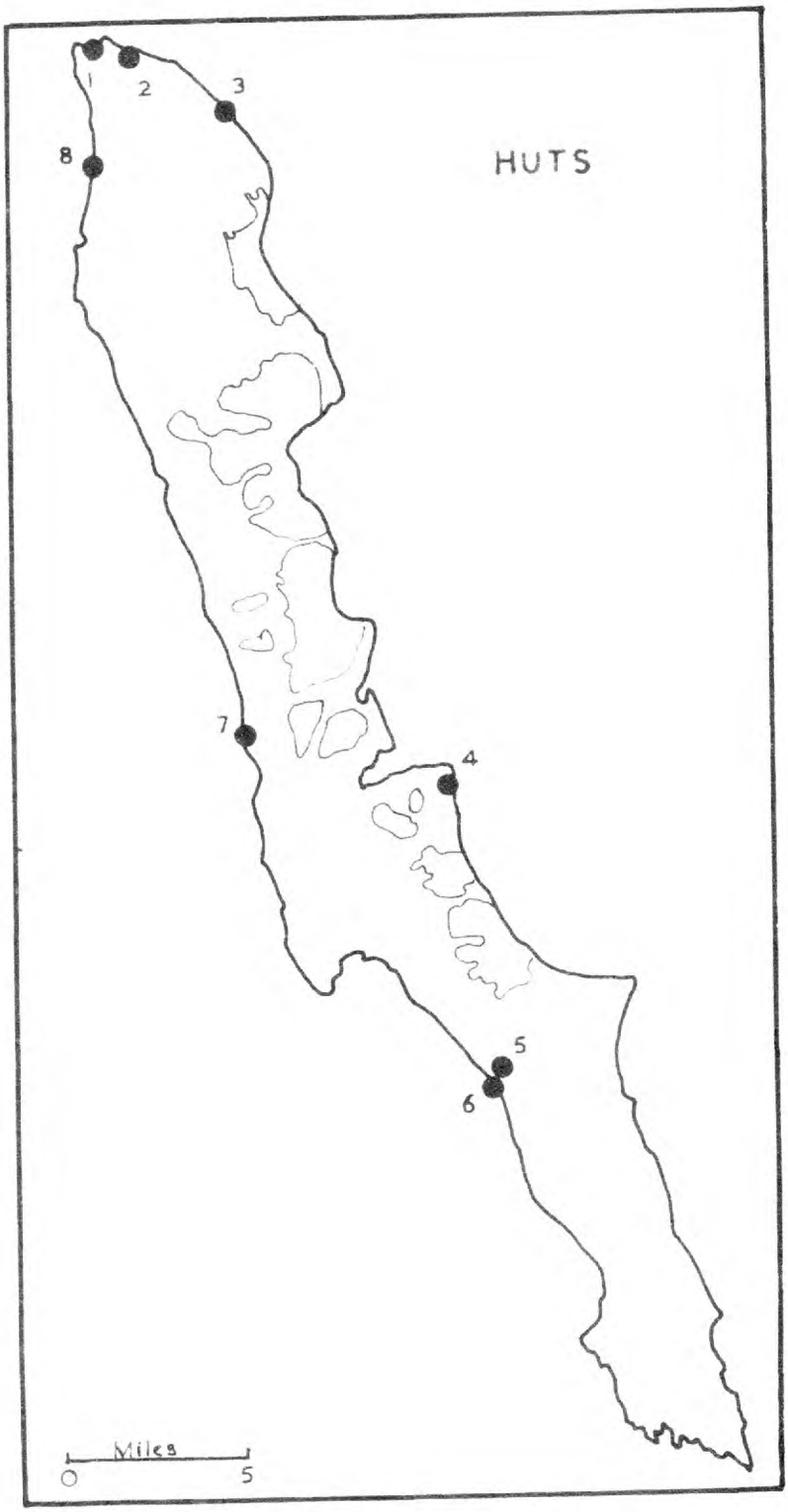
One of the most remarkable features of the Foreland is the 40square mile plain Forlandsletta which extends south from the end of the southern range, to the isolated group of hills at the southern tip of the island. Here the raised beach fringes of the two coasts meet over a distance of nine miles; the maximum level reaches only about 60ft. above the sea. The plain is covered with a well developed series of shore lines and beach deposits with only a few solid exposures (former reefs), now intensely broken by frost action. The mountains south of the plain, when seen from a boat south of the island, appear to be quite disconnected from the rest of the Foreland, and indeed were so when the sea stood 70ft. higher relative to the land than it does today.



Plate 8. Salfjellet from the south;
Methuenfjellet in the far distance.

This small isolated group of hills at the southern tip of the island consists of the rounded N-S ridge of Persiskammen (just over 1,000ft.), an indefinite area of broken ground between 300 and 700ft. high, and then the long rocky ridge of Salfjellet 1,310ft. (plate 8). Persiskammen is mostly scree covered but occasional outcrops of badly weathered schists occur : the east face of Salfjellet is by contrast very steep, great ribs of vertical limestone forming ridges which alternate with gullies of friable schist.

The raised beach fringe runs round the south end of Salfjellet and the island ends in a rocky headland surrounded by reefs - Salpynten - reminiscent of the way it begins, in the north.


HUTS
1
2
3
8
7
4
5
6
Miles
0
5

Huts.

There are six huts on the island in a state of moderate repair, and ruins of several old huts, for example at Andeneset, and just east of Kaldneset. Hut 1 (see diagram opposite) contains the equipment of the automatic radio beacon - Fuglehukbaken : there is a tiny outer room with two bunks and a small, but efficient stove. Hut 4, Kenmore, was built by one of the Scottish Spitsbergen Syndicate expeditions well over thirty years ago, but is still the largest and most comfortable on the island. (Plate 10).

Huts 2, 3, 5, 6, 7 and 8 are small trappers huts of various ages, mostly in poor repair. Number 3, at Mc-Vitiepynten (plate 9) can be made tolerably comfortable; the rest provide meagre shelter for a bivouac, but little else.

Weather.

To generalise from the three summers the writer spent on the island, the weather appears to go through three phases during the months of June to September. Throughout June and July the weather is fairly good - cold, sunny, with not a very great amount of cloud. Late July ushers in a period of violent gales, dominantly from the southwest, with almost perpetual low cloud, and much rain.

Snowfalls usually begin a week before the sun first dips below the northern horizon (the 27th August). There



Plate 9. The McVitiepynten trappers hut.



Plate 10. The hut at Kenmore. Central range in the background.

may follow a little cold fine weather, or the cloud cover and heavy precipitation of August may lead straight into the first heavy snowfalls of the winter.

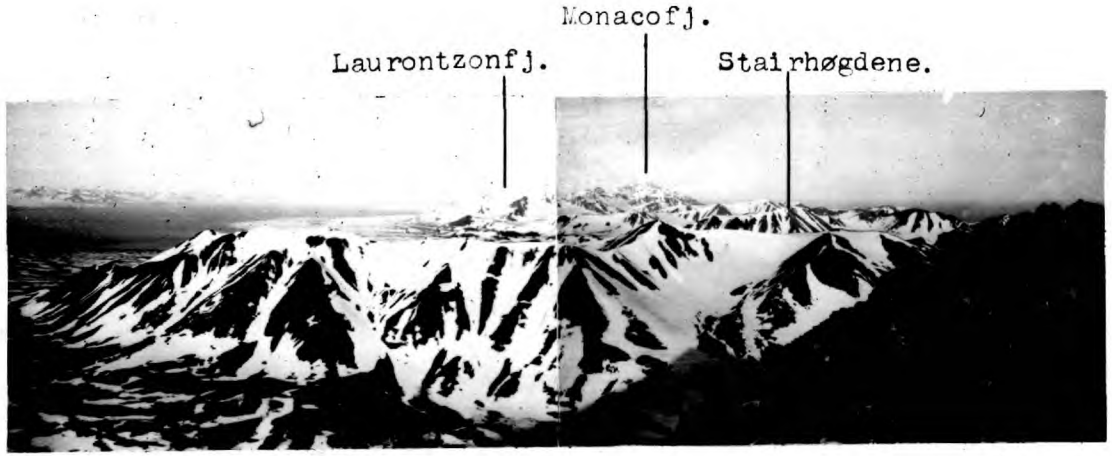
Good visibility then, may be expected at the beginning of the season and hoped for in early September, but the weather in August seems to be invariably bad.



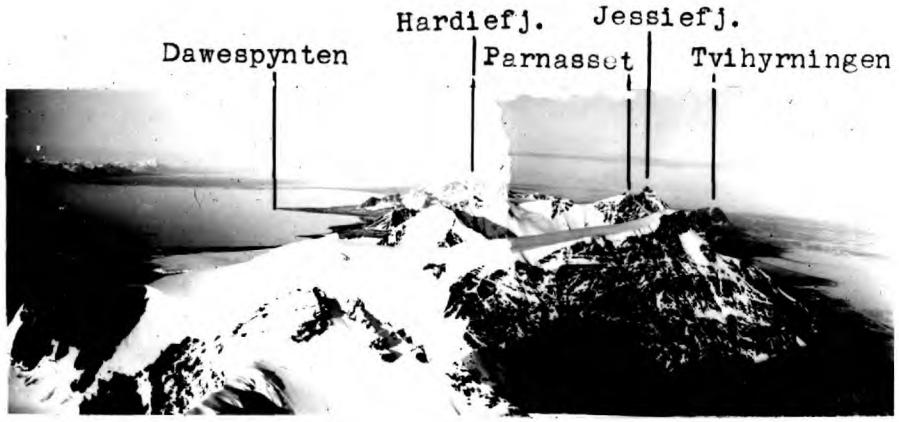
PANORAMA FROM 1 MILE WEST OF FUGLEHUKEN



FUGLEHUKFJELLET, FROM THE NORTH-EAST COAST

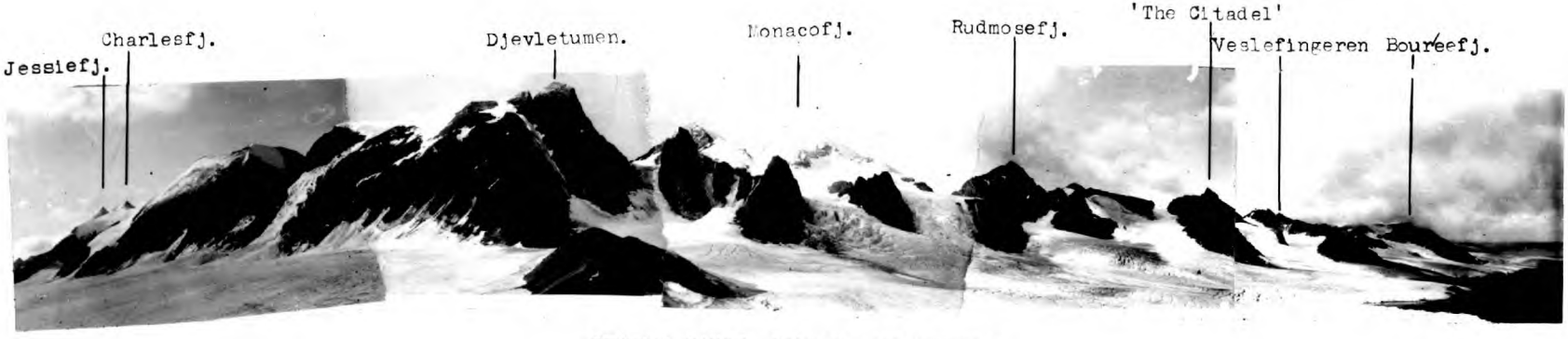


VIEW SOUTH FROM BARENTSFJELLET



VIEW SOUTH FROM SUMMIT OF MONACOFJELLET

(Phippsfj. in the foreground)

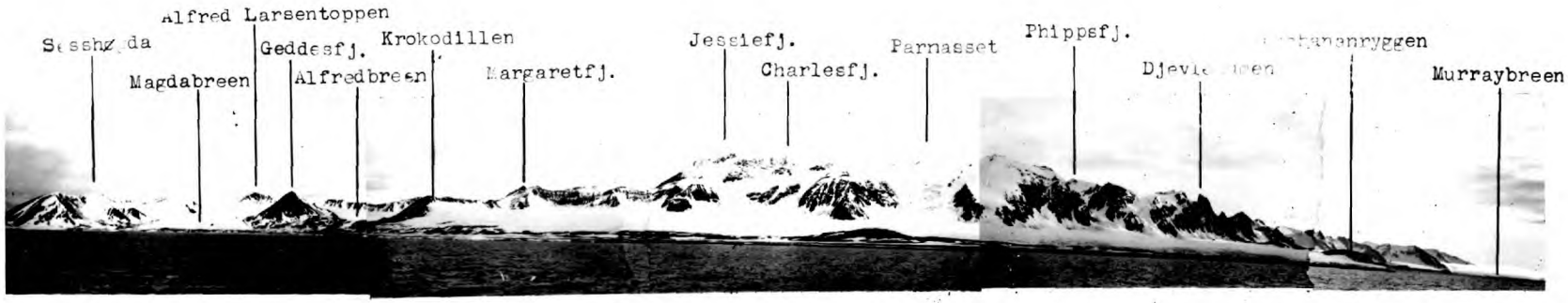


CENTRAL RANGE, FROM BUCHANAN RYGGEN.



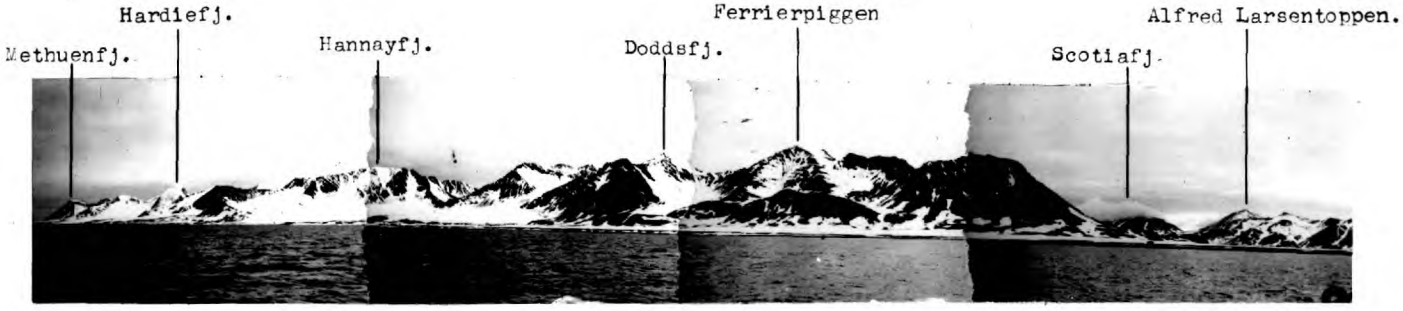
PANORAMA OF CENTRAL RANGE, FROM FORELAND SOUND.

PLATE 13 a) and



PANORAMA FROM FORELAND SOUND, E. OF ANDENESET

(Søre Buchananisen in the foreground)



SOUTHERN RANGE, FROM EAST OF DAWESPYNTEN

S.S.S. Hut visible on coast, at right.

PLATE 14 a) and b)

Previous geological work in Prince Charles Foreland.

Very little was known of the geology of the Foreland before this century. In 1874 R.von Drasche had published some observations on the west coast of Spitsbergen, and described two landings he made on the Foreland - at Salpynten in the south, and below the Sutorfjella in the N.W. He recognised the presence of rocks of the Hecla Hoek formation, and described the "breccia" of the Sutorfjella with an accompanying cross section to illustrate his view of the structure.

Two years later, in the Geological Magazine of 1876, Nordenskiold in a paper on the Geology of Spitsbergen refers to "the southern part of Charles Foreland" as one of the places where quartzites of the Hecla Hoek formation had been recorded.

However the first systematic investigation of the Foreland began in the summer of 1906 when Dr. W.S. Bruce led an expedition there under the auspices of H.S.H. Prince Albert of Monaco. Near Carmichaelpynten in the dark shales on the coast, poorly preserved plant remains were found, which Nathorst examined : they seemed to him "to prove the occurrence of the lowest sandstone series of the Tertiary although no absolutely sure conclusions can be drawn".

The presence on the island of a separate, younger formation, as well as the Hecla Hoek, had been

demonstrated, and the following year Bruce discovered more of these 'Tertiary' rocks at Reinhardpynten (Sword Point). However the principal activity of these expeditions was the topographic survey of the island, and this was eventually completed in the third summer - 1909. The map was published (in 1913) at a scale of 1: 140,000 (or 2.2 miles = 1 inch) and represented a considerable amount of very careful work. Whilst the position of the main features - mountain summits, prominent capes, and so on - were fairly accurately placed on the map, the work on detail was unfortunately, clumsy - so that the coast and the features of the mountains were very poorly represented. In 1909 and 1910 parties under the direction of the Norwegian Major Gunnar Isachsen carried out a further rapid survey using photogrammetric methods and a few additional theodolite observations. A much improved map of the island, this time at 1: 200,000 (3.1 miles = 1 inch) was published in 1915. The general lines of the greater ridges and corries were marked on this with sufficient accuracy to make it possible for later expeditions to plan their field campaigns to some extent in advance. But of course geological mapping of anything but a most rudimentary kind was still out of the question.

Meanwhile knowledge of the Foreland's geology was growing. The presence of Permo-Carboniferous strata was apparently established. G.W. Lee (1909) described in detail collections of Permian and Carboniferous fossils made

by Bruce in 1906 from localities south of Methuenfjellet : but the area was revisited in 1907 by Bruce and three others, when it was concluded that the blocks from which the fossils were obtained, were not in fact in situ, but glacial erratics. In 1909 Dr.Adolf Hoel also examined the area but found no Permian or Carboniferous beds in place.

Hoel in 1909 did, however, discover the presence of 'Tertiary' beds at Dawespynt, and on the coast below Buchananryggen at Trocaderostranda. He also recognised a series of N/S normal faults north of Selvagen by which the 'Tertiary' on the east was downfaulted relative to the Hecla Hoek (Hoel 1912: also note in Craig 1915).

In 1910 Nathorst published a comprehensive synthesis of the knowledge to date of the geology of Spitsbergen, mentioning the isolated occurrences of 'Tertiary' beds on the East coast of Prince Charles Foreland, and reiterating his opinion that the fossils collected by Bruce were from the lowermost sandstone series of the Tertiary.

Hoel in 1912 collected some molluscan remains from Selvagen, but these were never described.

The first attempt at anything like a systematic description of the geology of the Foreland was made in 1915. In August of the previous year, R.M. Craig had made a number of traverses with Bruce and a Mr.Koeppern over the northern-most third of the island and along the W. coast as far south as Jessiefjellet, as part of the work of the Scottish Spits-

bergen Expedition, led by Bruce. Craig (1915) summarised the results of this and all previous work in a paper to the Edinburgh Geological Society. The paper is divided into four sections ; Introduction - Topographic Features - Formations - Acknowledgements, of which the section on Formations forms the great part. He lists them thus :-

(d) (Peat
(Glacial Deposits
(Raised Beaches, Lagoons.

(c) Tertiary
(b) Conglomerate of North and South Sutors (Devonian)
(a) Hekla Hoek (Silurian) "

His description of the Hecla Hoek begins by referring to "organic remains found in these rocks on Bear Island, by Professor Nathorst ..... regarded as of Silurian age" - and he puts forward the Foreland rocks as presumably belonging to the same system. On the structure he writes that "in the northern half of the island, and probably in the southern also, these rocks are steeply folded and often overfolded towards the N.E. Their general strike is, therefore, N.W. and S.E., that is, their outcrops run obliquely across the island in that direction". There follows a brief description of the rock types which are dominant in various parts of the northern half of the island; thus, for example :- "the rocks of the Vogel Hook region (Fuglehuken) are mainly grits and quartzites, the latter white on a freshly broken surface, but weathering to a bright reddish brown". Craig recognised

that in the central range was a great thickness of quartzites "of Vogel Hook type", and he also mentions "several thick bands of a brecciated calc-chlorite schist" (presumably the brecciated slate with calcareous cement). From specimens collected by Bruce in 1906 and 1907, Craig concludes that the rocks in the southern half of the island are of the same formation, going so far as to comment on the similarity of specimens from Forelandsletta to the rocks he had seen near Richardlaguna, and to suggest that Rosshogdene in the far south "possibly include beds like those at Vogel Hook".

Despite searching "long and carefully", Craig failed to find any fossils in the Hecla Hoek rocks. He mentions that Bruce informed him that "in 1907 he collected what he considered to be specimens of graptolites from black shales in the Hekla Hoek beds from the shore in the vicinity of Mt Allan (Allanfjellet) and again N. of Cape Cold (Kaldneset). Unfortunately these specimens were lost". Bruce was not a geologist and no fossils have ever been found subsequently, so that no great importance is attached to this claim.

Under the heading of 'Conglomerates of N. and S. Sutors' (the Sutorfjella) Craig describes the "very coarse conglomerate" which forms the two summits, and makes the observation that it "does not extend more than ½ a mile N. of the N.Sutor and does not appear at all south of the S.Sutor, the whole visible exposure being confined to a strip about a mile long and from a ¼ to ½ a mile broad". He also notes

a "small exposure of much crushed and jointed greyish green and brown slate" on the beach in front of the S.Sutor, but "the relation of this .... to the conglomerate is not seen". The relation of the conglomerate to the Hecla Hoek rocks farther east in Mackenziedalen "could not be closely examined owing to the inaccessible nature of much of the high ground and to the great development of scree which masks the junction, especially at the foot of the slope. But, whether the plane of contact between the two at this particular part is a fault or an unconformability, it is steep (70° in the case of the S.Sutor, somewhat less at the N.Sutor), and it dips to the west; and there is certainly a marked discordance between the two". As might be expected from the nature of the deposit, no fossils were found and Craig concludes that "it is impossible to fix the age of this conglomerate more definitely than to say that it is younger than the Hecla Hoek series from the waste of which it has in great part been derived. It is most probably of O.R.S. age, and marks the very base of the system. Similar beds have been described from Red Bay in the north-west of Spitsbergen."

The brief account of (c)The Tertiary - covers only the exposures from McVitiepynten to Heemskerkneset, describing the rock types - "a rapid alteration of coarse and fine conglomerates, yellowish-grey sandstones, and black shales," - and the attitude of the beds : "the dip ... is to the S.E. and varies in amount, being from 30° to 40° at Point

Carmichael and decreasing gradually to Heemskerke Ness, there it is not more than 20°". Craig refers to the earlier discoveries of similar rocks further south, and concludes that "... lower Tertiary rocks occupy a narrow but continuous strip of the low ground on the east coast of Prince Charles Foreland..... at least as far south as Point Napier" (Dawespynten).

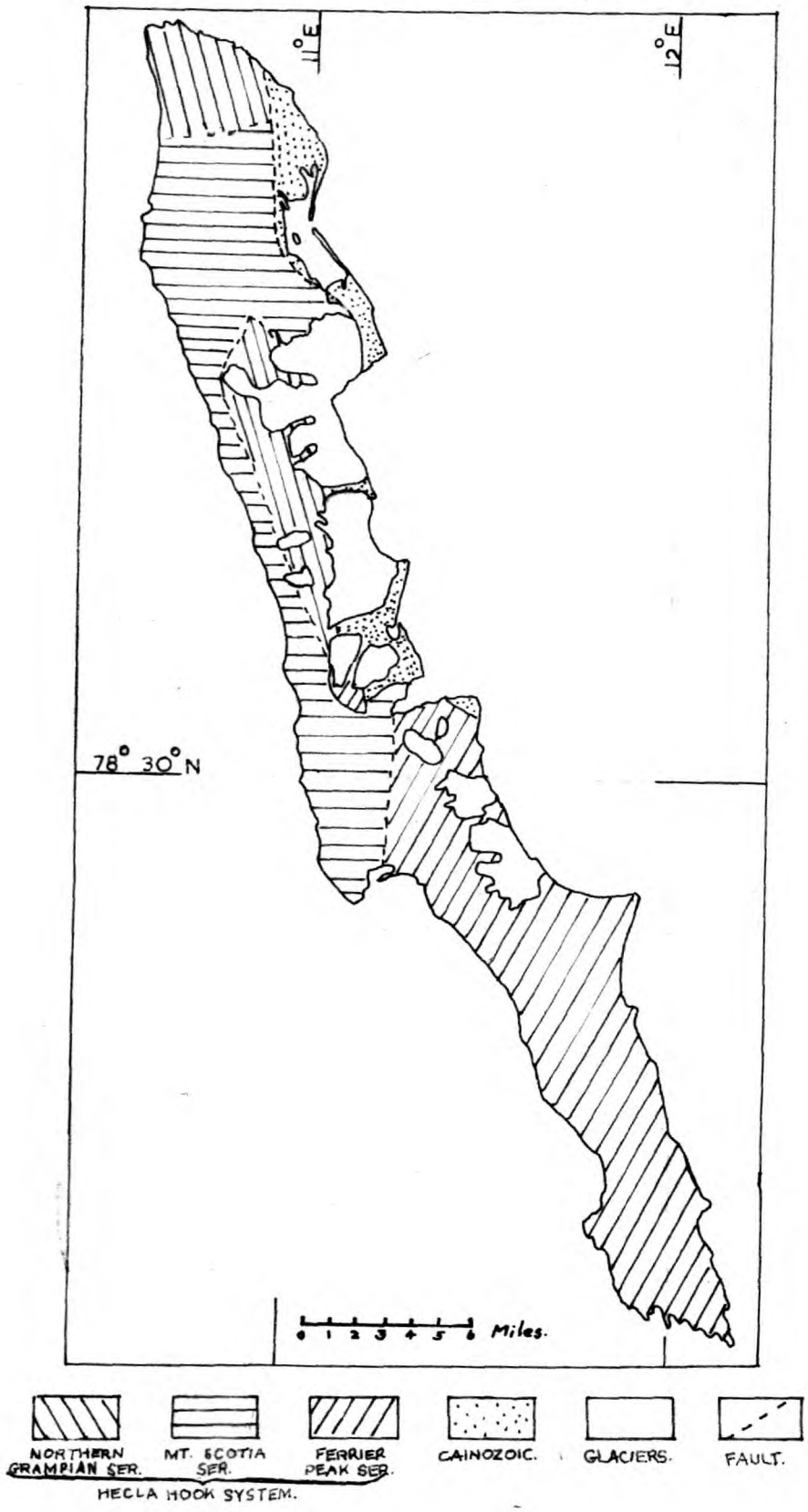
Members of the Scottish Spitsbergen Syndicate expeditions of 1919 and 1920 visited the island. Wordie included a few geological notes in his geographical paper (Wordie, 1921) but the bulk of the geological results were published by Tyrrell in 1924. Since this paper is the most recent comprehensive survey of knowledge of the Foreland's geology, it will be discussed in some detail.

Tyrrell's paper begins with a geographical description of the island, and a note on when, and with whom, the work was carried out. There are acknowledgements of assistance in the field to J. Scott, Prof.Charlesworth, J.M.Wordie, and D.A. Allan. A short "History of Geological Investigations in Prince Charles Foreland" follows, and a "List of Geological Literature relating to Prince Charles Foreland". In "Summary of Rock Formations and Structure", a paragraph covers the Hecla Hoek rocks, two paragraphs deal with the "Cainozoic rocks" of the east coast and there is a final paragraph on the conglomerate of the Sutorfjella. The Hecla Hoek is the next heading and this is dealt with in some detail. A ten page account of the observations in a narrative or geographical setting (titled "Details of Sections") is preceded by two pages in which a division into three "provisional and tentative" groups is suggested.

1. Ferrier Peak Series.
2. Scotia Series.
3. Northern Grampian Series.

It is important to note that Tyrrell here states plainly :- "It is not contended that this grouping serves for anything more than descriptive convenience. It is by no means certain whether these series are really separated, or whether the differences between them may not be accounted for by different stages or loci of metamorphism. If there is difficulty in delimiting these series of rocks, still less is it possible to state their relative ages with any degree

Diagram 5.



TYRRELL'S GEOLOGICAL MAP.

of certainty. Nevertheless, the lithological and geographical grouping given above serves as a convenient basis for present description, although it may be discarded in the future as a result of more detailed investigation". The distribution of the various series is shown on a map of the Foreland, reproduced here as diagram Opposite.

The proposed division is then elaborated by a few remarks on each series. The Ferrier Peak Series is said to consist of "dark bluish or greyish calcareous phyllites and fine-grained mica-schists, with lighter calcareous quartz-schists, and an abundance of dolomitic and ordinary crystalline limestone, white, light grey, or blue in colour. Other rocks occurring in lesser quantity are greenstone-schists and black slate. The predominance of carbonate rocks and minerals in this series is to be noted."

The rocks of the Mt.Scotia Series "are chiefly compact dark mudstones, often intricately veined with carbonates; grey, yellow, or white quartzites; and various types of limestone, often argillaceous and dolomitic, which frequently weather with a brilliant orange crust. Some of these limestones are black and slaty, one distinctive bed containing chert in layers and nodules", others are white or grey, and are usually siliceous and dolomitic. Other rock types occurring in smaller amounts are green slates, black carbonaceous slates, and a distinctive striped green and purple slate. The quartzites have often been mylonised, and the

slates puckered and cleaved, by intense mechanical deformation."

"The chief original rock type [in the N.Grampian Series] .... appears to be a finely banded rock consisting of alternate bands (usually much less than one inch in thickness) of arenaceous, argillaceous, and calcareous materials. The predominant arenaceous component has the grade of silt; hence the term siltstone, co-ordinate with sandstone and mudstone, appears to be appropriate ..... This banded type... has often suffered considerable autoclastic brecciation, with the formation of a slate-breccia ..... Along with these rocks are quartzites, graphitic slates, and pebbly sandstones, which have also undergone mylonisation in the neighbourhood of the greater thrust planes. In this formation there also occur numerous green stones and epidiorites representing original intrusions of basic igneous rocks".

These stratigraphical details have been quoted more or less in full, in order to show on what criteria the divisions proposed by Tyrrell were based. The detailed work that the present thesis is to describe has shown, as Tyrrell expected, that entirely new stratigraphic divisions are necessary.

The part of Tyrrell's paper entitled "Details of Sections" follows, giving accounts of several traverses in rocks of each of the three groups. Under "Ferrier Peak Series", there is a forefold division into notes on a) the Southern range, b) Forlandsletta and the far south,

c) the S. shore of Selvagen, and d) Alfred Larsentoppen (NW. of Selvagen). Apart from some errors in the identification of rocks - as for example in the opening description of the exposures on the coast south of Kenmore - the observations are accurate though not complete. Enough measurements of bedding are given to indicate the "simple anticlinal structure of the Napier Pt. [Dawespynten] area, and of the Peter Winters Cove tract ...." No other structural features are noted here however, apart from quartz veining, except on the south coast of Selvagen where "the great disturbances of strike and dip in this region are probably to be accounted for by a large shatter belt running near the southern shore of Ferrier Haven". Of the area around Alfred Larsentoppen, Tyrrell writes "this peak, and a small area to the south of it, appears to be the site of an infold of the Ferrier Peak Series within the Mt.Scotia Series ....", and later ; "how far the infold extends in the south and south-east, whether it connects up with the main outcrop on the south side of Ferrier Haven, and its exact relations to the Mt. Scotia Series, is unknown".

The Mt.Scotia Series is dealt with in five regions - Mt.Scotia (Scotiafjellet) itself; Conquerorfjellet; the area between Dyerlaguna and the northern part of the Thomsonfjella; the eastern part of the Thomsonfjella - north of Selvagen (Sesshogda); and the region about Richardlaguna.

The remarks on rock types are accurate as far as they go, but the structural observations are rather misleading. Thus of Scotiafjellet, J.M.Wordie, whose notes are quoted, writes: "the above (readings of 39° and 20°) were the only dip actually measured, and may cause misapprehension. Generally speaking, the dip is much steeper ... the tectonics are most complicated. The best section, that on the north-eastern ridge, gave the impression that one was dealing with 'concertina' structures". Tyrrell follows this up in the notes on the exposures amid the raised beaches east of Dyerlaguna, by saying "the dip is nearly always high, at least 60° to 70°, often vertical; only at one place was a dip as low as 30° noted. The direction of dip is alternately east and west, producing the "concertina" structure noted by Mr,Wordie in Mt.Scotia". Detailed mapping however has shewn that these alternations of dip to east and west do not represent closely alternating anticlines and synclines, but are variations in a single, nearly vertical fold limb. The beds do not 'young' first to the east and then to the west, but consistantly in the one direction, being alternately right way up and then slightly overturned.

The Northern Grampian Series is described in three sections. Part (a) "The region about Mt.Bouree" (Boureefjellet) is dealt with in some detail, considering its size. Most of the conclusions however are drawn from views of the "great southern cliff face ..... largely inaccessible owing to

vertical cliffs and ice" ; misidentification of rocks from a distance is frequent. Moreover the sketch section of the cliff is thoroughly misleading, with a complete failure to recognise the main structure. The traverse was carried out in a snowstorm, and presumably time for an adequate study was not available. The quartz-magnetite schist of 'Magnetite-Knoll' was noticed and fragments of similar rock are recorded from the local moraines. Section (b), "Mt.Jessie to Mt. Monaco" contains a mixture of errors with valid observations. It begins for example "Surmounting the black slates and quartzites of the Mt.Scotia Series on the western faces of Mt.Margaret and 510-metre hill, there is a thick band of dark green rocks which, in the great corrie north of Mt. Margaret, are seen to be greenstones, and green schists". In fact the green beds underlie "the black slates and quartzites" - and are dark green semipelitic and pelitic rocks. Wordie's unjustified remark on the "prominence of epidiorites in the Mt.Monaco section" has led to a vast exaggeration of the amount of igneous material in the mountains of the northern half of the island. The only important structural observation in this section is that "the western face of Mt.Jessie shows some extraordinary recumbent folding, which supports the view taken later on that a major thrust plane runs along the western margin of the range". (Presumably this refers to the southern face, not the western face which is parallel to the strike).

Part (c), the "eastern side of the Northern Grampians" is almost entirely concerned with the rock types found in the moraines of the glaciers on the east side of the central range. "The nature of the rocks can .... be inferred from the materials of the numerous moraines". There is a final paragraph on the rocks 'in situ' at the "eastern end of the Nunatak" (Buchananryggen) with a note of an exposure of a "curious rough-weathering, calcareous, slaty breccia, which, in thin section, is seen to carry numerous, newly-formed flakes of red biotite, suggesting contact metamorphism: .... this rock may have been hornfelsed by some undiscovered intrusion".

"Petrography" is the next large section of the paper, in which the rocks are dealt with in categories, thus:-

"I. Sedimentary Rocks.
1. Mudstones and slates.
2. Laminated, Banded and Puckered Siltstones.
3. Quartzites, mostly mylonised.
4. Dolomites and Limestones.
5. Quartz-magnetite-haematite Rocks.
6. Crush Breccias and Mylonite-Gneiss.
7. Hartschiefer.

II. Igneous Rocks intercalated with the ~~H.H.~~ Heckla Hoek Sediments.

III. Schists "

Not very much need be said of these sections. Under "Mudstones and Slates", the appearance of "ottrelite" is noted from only one specimen, found "as a loose block lying on the surface at the divide in Scotia Glen". A specimen

from the moraine of Murraybreen is described as a "fruchtschiefer" spotted with chlorite in a matrix of quartz and sericite. "These two rocks have every appearance of being due to contact metamorphism".

In the second section Tyrrell compares "these rocks composed of alternating bands or laminae of three distinct grades of coarseness, with the intermediate or silt grade predominant", with "the types known as fakes in the Scottish and other Coal Measures" Cataclastic effects are described in several specimens.

The section on Quartzites, deals with three mylonised examples from Conquerorfjellet, Jessiefjellet, and Bouree-fjellet.

In the section on "Dolomites and Limestones" the contrast is noted between the mylonites previously described and these rocks which "show comparatively little traces of the dynamic metamorphism which has affected other types of rock intimately associated with them ..... in some cases not even recrystallisation has occurred to any extent".

The quartz magnetite-haematite rocks "associated with the dynamically metamorphosed rocks of the Mt.Bouree region", are described; the view being taken that the specimens found in the moraines were derived from different beds from the one seen in "Magnetite Knoll". Tyrrell considers the rocks to be the result of "recrystallisation of pre-existing iron minerals in the rock during some stage of metamorphism",

rather than "the introduction of the iron-ore from outside.... by metasomatic replacement".

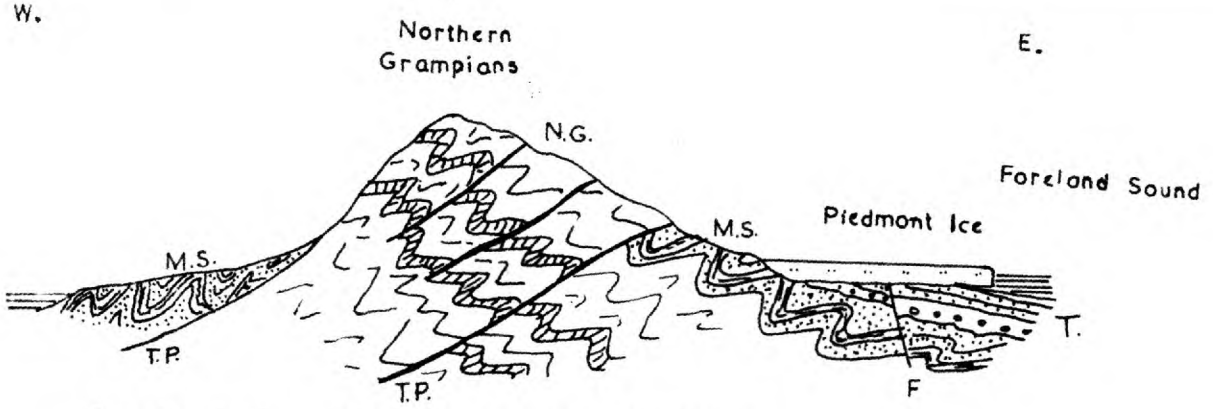
Part six deals with somespecimens of brecciated slates from the central range, and suggests a comparison with the crush breccias of the Isle of Man.

Under the heading 'Hartschiefer' Tyrrell describes a specimen of a kind of "flinty-crush rock" from the eastern flank of Mt.Bouree" and suggests the possibility of manufacturing this type of rock by extreme mylonisation of "at least three distinct rocks, namely, the banded siltstones, the quartzites, and the crush-breccias or conglomerates".

Igneous rocks are recorded from the moraines of Magdabreen, the corrie glacier north of Monacofjellet, and the glaciers "streaming north from the Ferrier Peak region". Examples are said to occur in situ in the corries between Margaretfjellet and Jessiefjellet, and on Monacofjellet. From the specimens the main lines of breakdown are noted, as the rocks become more schistose. Reference is made to the basic igneous rocks associated with the Hecla Hoek formation edsewhere in Spitsbergen, and it is suggested "that these pre-folding basic igneous masses characterise the whole of the Hecla Hook outcrop in Western Spitsbergen, and represent the "green rocks" involved in the Caledonian orogeny of Western Scandinavia".

The third part "Schists" covers the rocks south of Selvagen and east of Scotiadalen, that is the main outcrop of Tyrrell's Ferrier Peak Series', ranging in composition from quartz-schists to almost pure limestones - "The more schistose types of greenstone....also occur in this series". Specimens from various localities are described and Tyrrell concludes that the "description makes it clear that these rocks have been mineralogically reconstructed to a much greater extent than those described in foregoing sections. They are coarser, more schistose, and show no signs of advanced cataclastic deformation beyond a few strain shadows in the quartz. The higher grade of metamorphism may be correlated with the more open type of folding which prevails in this area ....., both phenomena probably being due to deformation under deeper burial than has obtained with the cataclastic types of the northern and central regions".

The penultimate section on the Hecla Hoek formation is entitled "Tectonics". Tyrrell begins by stating that "observations are still too scanty to elucidate the detailed structure of Prince Charles Foreland. In general, however, it can be said to be extraordinarily complicated, with folds, overfolds, thrusts, normal and reversed faults, and shatter-belts in bewildering profusion; a structure typical of an orogenic belt which has undergone one, and possibly two, periods of movement". The style of folding in the northern



Tyrrell's Section across the Northern Grampians.

M.S., Mt. Scotia Series; N.G., Northern Series; T.P. Thrust plane;
T, Cainozoic Rocks; F, Fault.

half of the island is contrasted with that of the main outcrop of the 'Ferrier Peak Series', where no recumbent folds or thrusts were observed, but instead a "rather open type of folding in anticlines and synclines". This, and the apparently greater extent of recrystallisation prompts Tyrrell to reiterate the idea that "the Ferrier Peak Series may represent the rocks of the central and deeper parts of the orogenic belt to which Prince Charles Foreland belongs; The Mt.Scotia and Northern Grampian Series representing the more marginal and superficial parts".

A "conjectural section" across the central range is given, and reproduced here (diagram 6). "In this the assumptions are made that the Mt.Scotia Series rests upon the Northern Grampian Series, and that there are two major thrust planes, one on each side of the mountain range. The basis for these assumptions are the less altered character of the Mt.Scotia Series (apart from mechanical deformation), and the unquestionable occurrence of intensely sheared and mylonised rocks, along with recumbent folding, in zones at the western base of Mt.Jessie, and in the region about Mt.Bouree on the other side of the range".

It is suggested that Conquerorfjellet "represents an overthrust block of the Mt.Scotia Series".

Finally it is stated that "in most places where the deformation can be studied it is clear that the overfolding and thrusting forces operated from west to east, a relation

Diagram 7.

North American Equivalents.	Bear Island.	Spitsbergen (Mainland)	Prince Charles Foreland.
Black River group .	Tetradium Limestone (Dark grey fossiliferous limestones).	Dark Limestone (common in Foreland Sound Region) - Holtedahl.	? Included in Ferrier Series.
Chazyan . . .	?	?	
Canadian . . .	Younger Dolomite Series (mostly dolomitic limestone with some calcitic limestone, occasionally with arenaceous, but more often with argillaceous impurities. Fossil nor.)	Younger Dolomite Series.	? Ferrier Peak Series.
	Slate (shale) Quartzite Series (grey, red, and dark shales interbedded with quartzite).	Slate - Quartzite Series.	Mt. Scotia Series.
Ozarkian . . .	Older Dolomite Series (Dolomitic limestones with oölitic, "oölitoid," and stromatolitic structures; becoming arenaceous towards the top).	Older Dolomite Series.	? Northern Grampian Series.

which holds elsewhere in the Hecla Hook rocks of the western mountain regions of Spitsbergen. All clearly displayed folds seen by the writer (Tyrrell) were overturned towards the east. Craig states that in the northern half of the island the rocks are steeply folded and often overfolded towards the north east ... but Wordie (1921) says that the overfolding is towards the west". To show that the principal direction of overfolding and overthrusting was in fact westwards, is one of the purposes of this thesis. The small folds observed which show an eastward overturning, are developed within the middle limbs of major recumbent structures, overfolded toward the west.

The final Chapter is "Correlation and Age". Tyrrell quotes Holtedahl's remark that "the Hecla Hook of Spitsbergen covers the same space of time as does that of the southern island (Bear Island), viz. the time from basal to Middle Ordovician, possibly (or probably?) with breaks", ; and considers it to be well founded, on a "lithological, stratigraphical and structural basis". To Holtedahl's lithological correlation of the rocks of Bear Island with those of the Spitsbergen mainland is added a "very tentative suggested correlation for the Prince Charles Foreland Series" (diagram No. 7).

It would seem to serve no useful purpose to comment here on anything but the extreme scantiness of the evidence

on which these correlations are based. A full discussion of the problem is left until after the new evidence has been presented.



Plate 15. The recumbent syncline of Puglshukfjellet, from 1 mile north.

The Present Work.

This thesis is the result of three expeditions to Prince Charles Foreland, made on each occasion by a party of two - Mr. R.A.McDonald, then reading Modern Languages at Cambridge, and the writer.

During the first expedition in the summer of 1950, a base camp was maintained at McVitiepynten on the N.E. coast, and work was carried out from there, and from two advanced camps established at Fuglehuken, and below the E. face of Barentsfjellet. The original plan to map the Hecla Hoek on an enlarged version of Isachsen's 1915 map proved impossible, and a new topographic survey had to be made. An area of 12 square miles, the northernmost part of the island, was covered, this area including Fuglehukfjellet and Barentsfjellet. The survey was at a scale of 3" to one mile. The Hecla Hoek and Tertiary rocks were eventually mapped on this basis, though this was not very satisfactory since the parts of the topographic map were not completely adjusted and integrated until the expedition returned. Almost all the geological work in the first two seasons had thus to be carried out on sketch maps, later to be adjusted to the final topographical base - an unfortunate but unavoidable waste of time.

In the quartzites of Fuglehukfjellet (plate 15) a large recumbent fold was mapped which was shewn by the



Plate 16. Frost crystals ; vertical cliff on N.E. Barentsfjellet.



Plate 17. Camp on the raised beaches.



Plate 18. East face of Charlesfjellet.

attitude of the sedimentary structures to be overfolded to the west and not to the east as expected. This prompted the planning of two further expeditions, to re-survey the island topographically, and to carry out a detailed geological investigation.

In 1950 ~~ten~~ eight weeks had been spent in the field, the island being left at the beginning of September. In 1951, we worked for a further fortnight - but then ran into the first blizzards of the winter which prevented our being picked up until the 19th September. By then the rocks were beginning to disappear under layers of frost crystals (Plate 16).

During this second season the whole of the rest of the island was explored - the southern half in less detail than the rest, which was mapped at 3 inches to one mile throughout, topographically and geologically. Depots were laid at the beginning of the expedition at Kenmore and Andeneset on the E. coast, and base was again established at McVitie-pynten. A backpacking journey was made from base to the west coast, and from a series of camps along the raised beach fringe (plate 17), all the mountains of the central range were successfully climbed. Almost stationary weather conditions, with cloud from 300 to 1,200ft. but magnificent visibility above this level (plate 18) enabled the survey of the western side of the range to be carried out most successfully.

This march converged on the Kenmore depot where further



Plate 19. Depot on Søre Buchananisen, at the foot of the mountain wall.



Plate 20. Upper parts of Monacofjellet, from the south.

supplies were picked up for a journey to the southern tip of the island, along the east coast. The southern range was examined and the general distribution of the major geological elements was elucidated, but a detailed solution of the problems in this area, had to wait until the third season. The depot at Andeneset was reached in mid-August and paddled to the edge of the piedmont glacier in an R.A.F.-type rubber dinghy, and there transferred to a sledge. The bare ice surface (plate 19, ~~page~~), inclined towards the sea, and crevassed at intervals of about 10 to 20ft. over large areas of our route, forced us to split the heavy load of food, equipment and rocks into two parts and relay them. The sledge - a 7ft. (ex-R.A.F.) Nansen-type - was otherwise continually overbalancing, and once on its side was an exhausting job to raise. The full load also made manouvering dangerous over bridges and along the thin ice walls where crevasses lay 'en echelon'.

When the northerly limit of continuous ice was reached, the rock specimens were paddled to a point just N. of Murraypynten, and left there to be retrieved by ship at the end of the expedition. The final 10 days were spent in the hills between Barentsfjellet and Glenbegdalen, and in re-mapping parts of Barentsfjellet and Fuglehukfjellet at a scale of 6" to one mile.

The final season saw the need for mobility, so that selected areas needing re-examination could be reached



Plate 21. The boat.



Plate 22. Snow cliffs at the coast.

quickly. For this purpose an 18ft. carvel built rowing-boat, (plate 21), was bought in Spitsbergen from a departing miner, and powered with a Seagull 3½ h.p. outboard engine. This was not a great success, the boat being admirable for the sea conditions, but so heavy that having to pull her above the high-tide level whenever she was beached, was unpleasantly exhausting. A smaller boat could not have carried all our gear, and would have failed to stand up to the heavy seas on the exposed western side of the island. An ideal combination would have been a light pram dinghy and a larger boat anchored off shore, with an inboard engine, (the outboard gave consistent trouble in starting in the cold water). The Scottish Spitsbergen Syndicate's hut at Kenmore was used as a base and the first part of the expedition was devoted to further examination of the southern range.

About four weeks were lost by a return to Longyearbyen for medical attention to a leg injury incurred in the mountains. After that, work in the areas accessible from base was soon completed and a final month's journey was made around the island in a clockwise direction, tying together loose threads in the geological pattern.

The fieldwork was completed in September 1953. The whole island had been surveyed in detail - McDonald working on the contouring of the mountains, the writer on the positioning of the mountains and details of the coast and rivers. The method used was a combination of plane-tabling and



Pl. 23. Plane table set-up.
Fuglehukfjellet.

compass triangulation, contouring was carried out with the aid of an Abney level and two "Watts" aneroid barometers, with vernier scales estimating to 1ft; three main points of the Norwegian theodolite triangulation were accepted as reliable for position and azimuth (Bourgeefjellet, Jessiefjellet and Methuenfjellet). Certain features of the coast, of the raised beach area of Forlandsletta and of the position of ice-fronts in 1936 were taken from low angle oblique air photos made by Norsk Polarinstitutt in that year. Details were plotted by a graphical method using a vanishing perspective grid.

Geologically the whole area was covered by detailed mapping; about 2,500 rock specimens were brought home to assist in building up a detailed stratigraphical column, and for petrological study. Continuity of exposure over large areas allows the various aspects of the geology to be studied in detail, and there fortunately is little need for conjecture and extrapolation.

The expeditions were organized with much encouragement from Professor H.H. Read and Dr. J.Sutton in the Geology Department, Imperial College, and from Assistant Professor A.Stevenson of the City & Guilds College, to all of whom sincere thanks are due. Grants were awarded by the Royal Geographical Society, the Linnaen Society and from the Central Research Fund of the University of London. The Watkins Award for 1951 was given for this research. The subsequent

laboratory work has been carried out at Imperial College during the two academic years 1952-54, with the aid of a University of London Studentship, and a supplementary award from the Department of Scientific and Industrial Research.

To all the bodies who have made this work possible, and the many firms who have supplied food and equipment for the expeditions, grateful acknowledgement is made.

PART II

THE HECLA HOEK FORMATION.

INTRODUCTION.

Rocks of the Hecla Hoek formation occupy the major part of the island, and are responsible for its mountainous topography. They have been strongly folded and are cut by numerous faults and belts of shattering. Despite the displacement of the faults, structures can be followed continuously, with the exception that the major fault through Scotiadalen throws rocks of two different tectonic levels into contact, and these structures cannot be correlated on the two sides of the fault.

In this research the first operation has, of course, been the unravelling of the structure, which - with the aid of evidence from sedimentation structures - led to the discovery of the original order of superposition of the various formations. In presenting the results, however, it is proposed to deal with events in the order in which they occurred : the history of deposition first, the structural complications afterwards. These two chapters are followed by one on the metamorphism: all aspects of the rocks, as such, are dealt with under these three headings. There follows a chapter in which the Hecla Hoek formation on Prince Charles Foreland is compared with the Hecla Hoek of other areas in Spitsbergen. In the final chapter of Part II, the Caledonian geology of Svalbard and the rest of the North Atlantic-Arctic province is discussed.

CHAPTER II. STRATIGRAPHY OF THE HECLA HOEK FORMATION.

North of Scotiadalen six major stratigraphical groups of rocks can be distinguished. Four of these, amounting to over 15,000ft. of sediments, form a continuous sequence, but structural complications prevent the other groups from being connected to this main succession.

South of Scotiadalen a series of thrusts breaks up the sequence, but a continuous succession of about 10,000ft. can be seen in the east, and there are two other allochthonous wedges of rocks, which give further successions of 2,000ft. In the far south of the island a succession of 9,000ft. of beds was recorded.

Incontrovertible evidence of the original order of superposition is scanty, sedimentary structures almost everywhere being lost as a result of the metamorphism and intense deformation. In one area in the north of the island, and at many points in the country between Scotiadalen and the west coast, however, current bedding and graded bedding are preserved. The succession can thus be determined at each end of the central range: in the centre ~~where~~ the structure is more complex, three-sided formations are common, and thick beds often disappear quite suddenly from the sequence as a result of movement and shearing.

Within the area of Map A., all the groups comprising the continuous northern succession are represented.

Essentially, the Scotia group, coloured blue, lies in the centre of a major synclinorium; the beds that outcrop north of this core are successively lower in the succession. Evidence of "way up" is seen at a height of 1800ft., on the ridge 2,600ft., south of the summit of Fuglehukfjellet. Here, in rather silty sandstones near the top of the Fuglehuk group, current bedding on quite a small scale can be observed - truncations resulting from changes of current, being spaced at an average interval of 1cm. The beds are unquestionably the right way up, and the Barents group lying above them is thus clearly shewn to be younger. The junction between the Barents group and the beds above (the Conqueror group) is a plane of considerable movement, as the mapping clearly shews. The Conqueror and Scotia groups above are, however, conformable, the latter being the youngest of the four groups. For evidence that the break between the Barents and Conqueror groups does not change the major sequence, we must turn to the south part of the central range and the area west of Scotiadalen.

Here the sequence :-

Scotia group.
Conqueror group.
Barents group.
Fuglehuk group.

is again seen, and current bedding within the Scotia group confirms that the group is the youngest of the succession.

South of Scotiadalen, no evidence of "way-up" of beds

is seen. The beds there will be dealt with, for convenience, in the order in which they lie at present. The rocks occuring north of Scotiadalen, which will be termed the Northern Division, are dealt with in the following pages as far as possible in the order in which they were laid down.

THE FUGLEHUK GROUP.

Beds of the Fuglehuk Group occur in three areas, all north of Scotiadalen :- as a block at the north end of the island; sporadically in the mountains of the central range; and over a large area north of Kaldneset.

The thickness of the series apparently exceeds 4,000ft. in the raised beach areas west of Scotia fjellet, but the base is never seen on Prince Charles Foreland.

A detailed succession was impossible to measure in the southern area, but in Fuglehukfjellet continuous exposure over large areas facilitated detailed mapping.of the following succession for the upper part of the series :

BARENTS GROUP.- supra jacent

F.21. 100ft. Shales with two 15ft. bands of massive quartzite in the lower part.
F.20. 10ft. Quartzites.
F.19. 80ft. Shales with thin quartzites interbedded.
F.18. 45ft. Quartzites.
F.17. 5ft. Shales.
50ft. Quartzites.
20ft. Quartzites and shales.
F.16. 60ft. Quartzites.
F.15. 70ft. Shales, with quartzites.
F.14. 25ft. Quartzites with shales interbedded.
35ft. Quartzites.
F.13. 4ft. Conglomerate.
10ft. Quartzites.
6ft. Conglomerate.
8ft. Quartzites.
30ft. Conglomerate.
5ft. Quartzites.
10ft. Conglomerate.
F.12. 64ft. Quartzites and shales interbedded.
14ft. Quartzites.
30ft. Shales, with ~~little~~ thin quartzite and conglomerate bands.
F.11. 50ft. Quartzites.

F.10. 20ft. Conglomerate and quartzite.
20ft. Conglomerate.
F.9. 180ft. Quartzites with a band of 10ft. of interbedded shales and quartzites at 80ft. from the base.
F.8. 47ft. Shales and quartzites :-
15ft. Shales.
5ft. Shales and quartzites.
15ft. Quartzites.
12ft. Interbedded shales and quartzites.
F.7. 55ft. Quartzites.
F.6. 30ft. Shales and quartzites :-
10ft. Interbedded shales and quartzites.
10ft. Quartzites.
5ft. Interbedded shales and quartzites.
5ft. Shales.
F.5. 250ft. Massive quartzite and some pebble bands.
F.4. 80ft. Shales with quartzite interbedded.
F.3. 200ft. Quartzite.
F.2. 50ft. Shales with a few quartzite bands.
F.1. 20ft. Quartzites.

In the extreme north-west of Fuglehukfjellet a further 260ft. from a lower part of the group is upfaulted, but its connection to the main succession above is unknown :-

F.b. 200ft. Massive quartzites with three thin shale zones of a few feet in thickness.
F.a. 60ft. Alternating quartzite and black shale bands, a few inches thick.

The total thickness is thus in excess of 1,980ft. of that amount 76% is made up of quartzite, 19% of shale, and 5% of conglomerate.

There are no perceptible variations in the facies of the group in different areas. The massive quartzites everywhere give rise to steep crags, such as the 75° face a thousand feet high on the north side of Charlesfjellet: compare plates 15, page 36 and 24, p.100. On the coastal plain

the contortions of the raised beaches around old stacks and reefs demonstrate the resistance of the quartzites to sea action; nowhere else does such a great amount of bare rock appear through the raised beach deposits and the modern coast has its complement of small islands and jagged headlands.

The quartzites are compact quartz sandstones, usually light grey when fresh, a pale or medium brown on weathering: Some are a dark grey and weather grey. They are hard and massive, not closely jointed, but cut by shearplanes.and many polished and slickensided surfaces where small scale movement has occurred. Bedding is very rarely visible unless shale intercalations occur.

The shales are always black: they often occur as thin laminae in the quartzites, but occasionally reach a thickness of up to 50feet. They weather black.

An uncommon rock-type which has been included in the shales of the table above is a banded siltstone, light to dark grey when fresh; the coarser, more quartzose bands weather brown, and exaggerate the lithological differences. Graded bedding is very frequently shown up in this way; the thickness of a single graded bed averages two or three centimetres, the coarser base of each bed contrasting sharply with the fine grained top of the previous bed, and itself becoming gradually finer upwards.

The conglomerates usually appear much distorted in hand specimen and when weathered often resemble crush breccias.

They are generally grey, weathering to brown.

From the Fuglehuk group come slides No:- 235, 391, 435, 530, 1149, 1841, 1910, 1911, 1913, 1922.

Typical of the quartzites are 1922 and 1149. The former, from the coast west of Ormondryggen, shows a sutured intergrowth of grains varying in original size from 0.5 mm. to 0.002 mm., with two common diameters - 0.4 mm. and 0.1 mm.-grains of the latter size forming a matrix which surrounds the larger quartz grains. The matrix contains small interstitial carbonate granules (about 6% of the total). A single grain of zircon occurs in the slide.

1149 from the east face of Margaretfjellet is more cataclastically deformed. Most of the original quartz grains - now rather flattened - had a diameter of something between 0.5 and 1 mm: a few are much smaller (down to 0.1 mm). Small interstitial grains of carbonate occur, some having recrystallised to form larger units: the total amount is about 2%. A few small grains, of strongly twinned plagioclase occur - the composition is roughly An.30, that is Oligoclase. This makes up far less than 1% of the rock.

Other slides show very similar features - a small amount of carbonate material is general, very minor amounts of plagioclase occur, and the accessories are schorlite - commonly, and zircon less frequently. Slide 1418 from the northern part of Fuglehukfjellet is unusual, showing very well rounded quartz grains in a matrix of about 20% carbonate,

80% quartz.

The shales show very little in section. Slide 1841 from west of Scotiafjellet is a fine grained silty shale with minute grains of quartz. 1910 similarly shows a few quartz grains in a very fine grained matrix.

The various conglomerate horizons are very similar, pebbles ranging in size up to 3 cms. but rarely larger. In slide 591 the pebbles are of fine grained dolomitic limestone and of medium grained quartzite in which the average diameter of grains is 0.15 mm. The quartz shows strong strain shadows. In one pebble of quartzite is a grain of albite. The matrix is composed of 50% quartz and 50% calcite. The quartz grains are very angular; about 0.5 mm. across; Calcite grains are interstitial. One small grain of microcline appears in the slide.

Siliceous limestones are extremely rare in the Fuglehuk group but bands of between 6 and 10 feet thick were noted on Rudmosefjellet, near the central peak, and on Parnasset, very close to the summit (on the west ridge). Since both these occurrences lie in strongly folded overthrust blocks it is not possible to say just where in the succession they occur. Specimen 435 from Rudmosefjellet is typical - a speckled light and dark grey crystalline limestone weathered to a strong orange-brown colour. In thin section it shows few signs of original sedimentary textures - a former quartzose band shews as a zone of inter-

locking grains, partly "floating" in the recrystallised carbonate material which is dolomite: the crystal size of this latter now averages 2 mm.

Towards the top of the group in the region between Jessiefjellet and Margaretfjellet and again - at a much lower level in the group - west of Scotiafjellet, there occur thin bands of an unusual sediment. This is a compact light or medium grey gritty rock, weathering orange-brown. Thin sections (570 and 571) show large grains of quartz in a medium grained calcite matrix; the grains are up to 1 mm. in diameter, averaging 0.4 to 0.5 mm; most of them are single grains, a few are fragments composed of two or three grains, and some are fragments of mylonised quartzites. None of the grains are well rounded. There is a single grain of felspar, simply twinned. The matrix is largely carbonate granules - with a few small quartz grains - fine-grained (average diameter 0.1 mm), partly recrystallised. Of the whole, 20% is quartz, the rest is calcite.

THE BARENTS GROUP.

The group outcrops persistently in the area north of Scotiadalen. An examination of the maps and profiles immediately shows how immensely variable in thickness is the group. The rocks are almost all incompetent, and the group lies between two thick quartzite-slate series, a coin-

cidence of misfortunes which has rendered the elucidation of the original succession almost impossible. The thickest and least distorted section is seen in north Barentsfjellet, (profile A4) but isoclinal overfolding is intense and the problem is difficult even with the help of the 6" map (F).

The succession is as follows :-

OVERTHRUST CONQUEROR GROUP.

B4. Dark grey or purple-grey slates and silty slates often laminated, with bands weathering to slightly different shades of purple grey and brown, presumably according to varying amounts of impurities.
This part of the groupnis lettered B4 on the maps and coloured purple-grey. Profile A4 illustrates the variation in apparent thickness - from 240ft. to 1600ft., at different points below the overthrust Conqueror beds. Probably the original thickness was exceeded something between 600ft. and 1,000ft. - but the top cannot be identified.

B3. A continuously fine grained series of slates, and subordinate siliceous limestones, - weathering to a characteristic orange and green colour. The slates are thinly banded with slightly siltier beds. The thickness is probably from 1,000ft. to 1,200ft. : "B3" on the maps.

B2. A green quartzite band weathering grey-green, which varies in thickness in different limbs of the folds, from 35 feet to zero.

B1. About 440ft. of dark green slates, with several green quartzite horizons in the lowermost 100ft. - some of them with pebble bands. A further 20ft. horizon of green quartzite at 200ft. from the base is indicated on map F (on the lower part of Barents NE ridge).

FUGLEHUK GROUP.

(The total thickness of the Barents Group exceeds 2,300ft. here).

In the Sutorfjella occurs a sequence of green slates and quartzites identical to those of numbers one and two of the Barentsfjellet succession. The thickness exceeds 1400ft., the base not being seen : above them lies the Sutor conglomerate. That they are clearly part of the Barents group is shown in more detail in the structural description - page 93 . The conglomerate exceeds 400ft. in thickness, but is not uniformly coarse throughout. In much of it the pebbles are about 4 to 5 cms. across; occasionally blocks reach 2ft. The majority of the pebbles (80%) are of pinkish quartzite when broken open often showing concentric zones of weathering/leaching (eg. specimen 1399A). Next most common are fragments of green slate; the rest are green, grey and brown quartzites, some veined quartz, and some light buff limestone blebs.

The matrix (slide 1399B) is composed partly of large quartz grains (very variable in size, averaging 0.8 mm. in diameter) and a mush of green shaley material. Clearly this component of the matrix, and the numerous green slate fragments are derived from reworking of the beds below: deposition of this fine green material seems to have been persistent. The fresh material - the pebbles and large quartz grains-have a far more erratic distribution and were presumably supplied sporadically.

In the northern part of the island, there can be made out a striking difference in the successions, for in

Barentsfjellet only a few minor disconformities occur, represented by thin conglomerates. The conglomerate of the Sutorfjella must represent a major interruption in sedimentation with considerable reworking of beds just deposited.

In the mountains south of Laurentzonfjellet, and as far south as the Barents group extends, the rocks are intensely distorted. The thickness varies immensely; on Monacofjellet for example in the middle limb of the anticline it is 80ft.; on the crest it is 1,100ft.

A brecciated siliceous limestone formation described in the section "Cataclastic Effects" - p. 104., is identified as equivalent to part 3 of the Barentsfjellet succession. It persists throughout the area between Murraybreen and Scotiadalen. In the mountains around Jessiefjellet a thin formation of dark green slates occurs - cut out by thrusting to north and south - about 200ft. thick. This may be equivalent to part 1 of the northern succession. These two identifications, however, are somewhat uncertain because of the intense distortions involved in the folding and thrusting.

Slides of rocks of the Barents Group are numbers :-

102, 108, 113, 119, 121, 124, 128, 202, 241, 255, 290, 385, 406B, 407, 495, 562, 1150, 1152, 1155, 1217, 1254, 1258, 1312, 1338, 1356, 1358, 1362, 1365, 1383, 2192.

THE CONQUEROR GROUP.

Rocks of this group outcrop over very large areas of the island, north of Scotiadalen (Maps A,B,C and F).

The maximum thickness, 4800ft. is developed in the Charles anticline, west of the peaks south of Margaretfjellet (cross section C5). Since the beds are lying on the crest of a recumbent anticline, this is almost certainly an exaggeration of the original thickness. Elsewhere, as a result of thrusting the thickness varies greatly : on Conquerorfjellet itself for example, the group totals only 1800ft.

In the area of maximum thickness, much of the succession lies below the raised beaches of the west coast plain. On Barentsfjellet (Map F), however, the upper junction with the Scotia group is undisturbed, and the stratigraphy of the upper part of the Conqueror group is as follows :-

SCOTIA GROUP.

C9. 10ft. shales.
130ft. shales with dark quartzite bands.
C8. 60ft. quartzites.
C7. 40ft. shales.
C6. 60ft. dark quartzites.
C5. 30ft. shales with quartzite bands.

THRUST

C4. 60ft. dark quartzites.
C3. 20ft. shales with light quartzite bands.
C2. 40ft. grey quartzites and conglomerate bands with pebbles up to 3" across.
C1. 900ft. black shales, with occasional light quartzite bands - two conspicuous bands, of 20ft. at 290ft. from the base, and 10ft. at 610ft. from the base.

THRUST

BARENTS GROUP.

The thickness here totals 1350ft. Perhaps about 3500ft. are missing, but lateral changes in the thickness of this group might well occur; they could not be discovered because of the structural complications. Cross sections A5 to B3 illustrate the variable thickness the Conqueror group displays in the upper structural unit. Nowhere in this unit does it exceed 2500ft.: but it is always apparent that some part of the succession is cut out by thrusting.

What is probably the lowest 1100ft. of the succession is exposed on the western slopes of the hills west of Alfredbreen and Magdabreen. The lithology is exactly the same as on south Barentsfjellet - thick zones of slate and quartzite alternating. Number C1 of the Barentsfjellet succession (900ft. of slate with very little quartzite) is not present, and is probably much higher in the succession than are these rocks. As profile C5 shows, a traverse up the hillside is equivalent to a traverse down the succession, which is as follows :-

200ft. Dark quartzites with frequent intercalations of black shale.
100ft. Intercalated black slate and quartzite.
350ft. At the top, alternating quartzite and shales, becoming more quartzose towards the base.
20ft. Massive quartzite.
200ft. Black shales, with a few quartzite intercalations.
20ft. Massive quartzite.
10ft. Black shales.
150ft. Quartzite, with shales intercalated.
50ft. Shales, with a few quartzite intercalations.

BARENTS GROUP.

It is almost certain that a great part of the top of the Barents Group is missing, and probably, therefore, the succession above does not reach down to the lowest beds of the Conqueror group.

On Conquerorfjellet both the upper and lower limits of the group, are dislocations - profile C7. The general lithology is exactly similar to that developed elsewhere. On the summit a conspicuous 12ft. bed of conglomerate occurs, and about 20ft. lower in the succession, an unusual calcareous grit is found, 3ft. thick.

The conglomerate is typical of several conglomerate horizons noted elsewhere in the group. Pebbles average 2 to 5 cm. across, occasionally are as large as 10cm.; they are well rounded, all of quartzite. In slide 635, the pebbles are seen to consist of fine grained quartzites - containing a few grains of plagioclase and of siderite (after dolomite?) : the average grain size is 0.1 mm. The matrix is coarser, grains averaging 0.2 mm. in diameter and reaching 0.4 mm. ; they are not very well rounded. Quartz makes 96% of the rock; 4% is of dolomite, which in the matrix is seen altering to siderite along grain boundaries and twin planes. 338 is a conglomerate from west Barentsfjellet. The pebbles locally reach 9 cm. in diameter, but are generally about ½ to 1 cm. across in the thin section cut: most are extraordinarily angular. They consist of fine grained quartzites - completely recrystallised and

seen to be greatly strained under crossed nicols; medium grained quartzites - little strained; and limestone - very fine grained and pure - in which slight variations in coarseness (in the region of 0.05 mm) indicate bedding: the limestone is of calcite, recrystallised in part, forming crystals of 0.1 mm. The matrix consists dominantly of well rounded quartz grains (up to 0.6 mm, averaging 0.4 mm) and dolomite grains, largely recrystallised around the quartz grains, but probably originally averaging 0.3 mm. to 0.4 mm. in diameter. Carbonate makes 50% of the matrix.

The quartzites are dark grey, gritty - textured rocks; they weather grey or an insipid brown. Slides 559 and 192 are fairly typical. They contain about 10% of argillaceous material - the rest is quartz, with occasional grains of plagioclase and schorlite as accessories. The matrix of 192 is very fine grained - two thirds quartz, one third clay; possibly carbonate material is present for there is some iron staining. In this matrix lie beautifully rounded grains of quartz (up to 0.4 mm) mostly single grains, a few cemented together: there are only occasional signs of strain in the quartz. This sediment is probably a reworked quartzite and may well have been derived from lower parts of the Conqueror group itself. The characteristic presence of argillaceous material is a sign of poor sorting: this is the strongest and most significant point of difference between the rocks of the Conqueror group and the Fuglehuk group.

The shales are black, and weather black or brown. In thin section (eg. 1351) they show very little - tiny quartzite grains in extremely fine grained clay material, showing bedding.

In contrast to the Fuglehuk group gradations between quartzite and shale occur in the Conqueror group fairly extensively - dark grey, silty, laminated rocks.

Of the unusual rocks occurring in the series, the calcareous grit of Conquerorfjellet has already been mentioned. It is a dark grey rock, weathering brown, with quartz grains standing out on the weathered surface. In thin section 637 the matrix is seen to be recrystallised calcite in which lie fairly well rounded grains of quartz, occasionally of plagioclase, and a few large fragments of quartzites - containing plagioclase. The quartz is very strained throughout. The composition is 40% quartz, 58% calcite and about 2% of siderite after dolomite. Very similar rocks occur extensively in the area of the upper structural unit, in the uppermost 100ft. of the Conqueror group.

An unusual siliceous limestone (specimen 1339) occurs north of Laurentzonfjellet on the strip of rocky ground between the two large lakes there. Ten feet thick, lying between quartzite horizons, it is 60% carbonate, 40% quartz. The horizon is just above the junction with the Barents Group (a slide) seen in the centre of profile B2.

Slides of rocks of the Conqueror group are numbers :- 192, 338, 493, 559, 608, 609, 635, 637, 972, 1321, 1328, 1339, 1351, 1397, 1398.

THE SCOTIA GROUP.

This group outcrops extensively north of Scotiadalen, especially in two areas - the great syncline of Taylorfjellet and the mountains just south, and as a strip running obliquely across the island from Dyerlaguna, through Scotiafjellet, to the north side of Scotiadalen.

The top of the group is never seen in the northern syncline, and is cut out in the Southern outcrop by a great overthrust carrying this group onto the Fuglehuk group. The maximum thickness definitely seen in the northern syncline is 3900ft. West of Conquerorfjellet the thickness is 5800ft. but repetition by the thrusting, and thickening in the core of the Charles anticline may make this figure too high an estimate. Clearly, however, the thickness exceeds 4000 feet.

There are very rapid alternations of shales and black limestones in the group, and a detailed succession would be very difficult to measure. In addition much of the detail on any traverse is lost, for the rocks disintegrate into scree very easily.

In the northern syncline the group falls into three parts, an "upper part" and a "lower part" on either side of

a formation of black slates 500ft. thick.

At the base of the group the special facies developed at the junction with the Conqueror group is remarkably persistent over the area of Map A and the northern part of Map B. The junction is clearly seen in several places (on south Barentsfjellet, north Balfourfjellet and Leefjellet for example). Above the slatey top of the Conqueror group lies a zone of calcareous grits about 10ft. thick - dark grey rocks weathering dark brown, with quartz standing out on the weathered surfaces . In thin section 310, from north Balfourfjellet the grains are seen to be quartz, angular and intensely cracked, in a recrystallised mass of dolomite : under very low illumination the outlines of the original detrital carbonate grains show up. The average grain size is 0.8 mm. and 0.6 mm.- quartz and carbonate respectively. The composition is 50% quartz, 50% dolomite.

On Leefjellet shales of the Conqueror group are followed by 10ft. of conglomerates, 20ft. of black shale, 4ft. of conglomerate, 15ft. of black shale, and then 5ft. of calcareous grit similar to the rock described from Balfourfjellet.

These conglomerates are composed of pebbles of quartzite up to 7 cms. in maximum dimension, set in a fine grained carbonate matrix with a small amount (about $\frac{1}{8}$) of fine quartz. The pebbles (slide 1331) are of rather 'dirty' (ie. argillaceous) quartz sandstones - exactly like those

of the Conqueror group below.

The calcareous grits suggest reworking of sediments of the Conqueror group, while fresh detrital carbonate material was being added. The conglomerates of Leefjellet are more drastic indications of the same conditions. The two series are disconformable, and erosion of the top of the Conqueror group preceeded the formation of the Scotia group, and provided material for the basal part of that group. At the same time the composition of the detritus brought into this area of sedimentation changed markedly. The dominant role of quartz was taken over by carbonate.

The lowermost 600ft. of the Scotia group consists of black slates, with occasional thin beds of limestone and gritty limestone making about one tenth of the sequence. The limestones are always black or very dark grey, and often oolitic. Slide 347 from Barentsfjellet for example, shows dolomite oolites averaging 1 mm. in diameter, in a calcite matrix too fine to resolve even under a high power objective. Many of the oolites have very small (silt grade) quartz grains at their centres. Others show rings of a dust of authigenic iron ore - magnetite, or possibly pyrite - surrounded by a further zone of carbonate growth. The composition is 99% carbonate, 1% quartz.

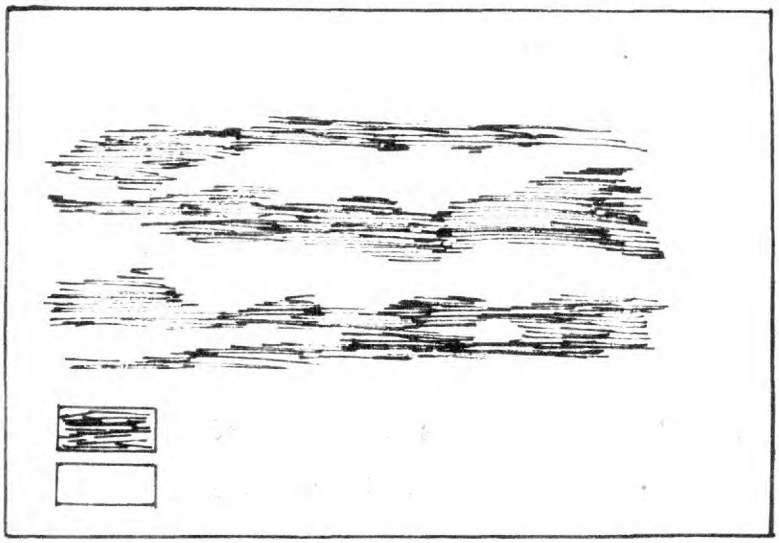
Slide 354 from south Barentsfjellet shows large clots of carbonate grains and smaller single quartzite grains set in a very fine carbonate matrix. This and the rock

described above clearly indicate sedimentation in very shallow water conditions, with reworking and much chemical precipitation of carbonate material.

The incidence of oolitic limestone dies out upwards, and the rest of the 'lower part' of the group consists of black slates with thin bands (six inches or more in thickness) of black, cryptocrystalline dolomitic limestone. The slates weather black and white, the limestone a soft grey. Limestones probably make up half to a third of the succession. Frequently they contain blebs and layers of chert - invariably cryptocrystalline and standing out a conspicuous jet black on weathered surfaces. The blebs rarely exceed 2 cm. in maximum dimension; and are often, though not always, aligned parallel to the bedding of the limestone.

The central slate formation lies about 2100ft. above the base of the group in the Taylorfjellet-Stairhogdene area. The thickness is roughly 500ft.- the rocks being black slates only.

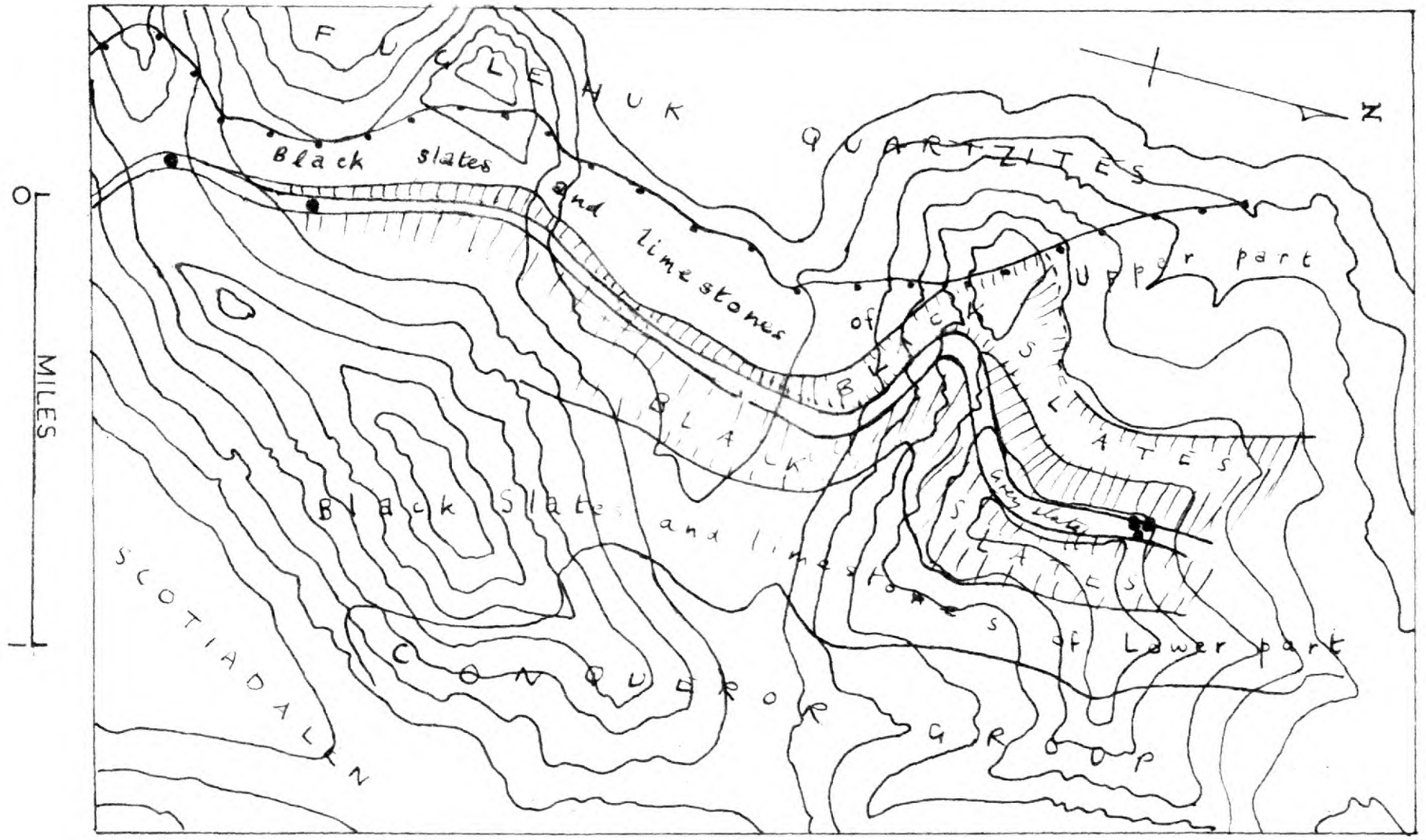
The upper part of the group is lithologically similar to the lower part. Black slate and extremely fine black limestones alternate, the latter being subordinate in amount. The limestones throughout are too fine-grained to resolve under high power - and their composition can only be assessed where they are seen recrystallising in patches.



Slides 1866 and 1867 (actually from the southern outcrops) serve to illustrate this well. (Microphotographs, plates 27a and b). As diagram 8 shows, they are from the same thin bed of limestone, 3 inches apart, and it is clear that 1867 is the result of recrystallising the material of 1866. The composition of the cryptocrystalline limestone is so determined.

The lithological development of the group in the southern outcrop, which includes Scotiafjellet itself is identical to that in the north. Again a three-fold division is discernible, and the rocks of the 'lower' and 'upper parts' are very similar in the two areas apart from the occurrence in the south of rather larger chert blebs reaching up to 20 cms. in maximum dimension. Many of the blebs are oval, but some very irregular ones suggest that not all of this chert is of primary origin. In thin section the chert is cryptocrystalline but in it can be seen numerous small rhombs of dolomite. In the lowest hundred feet of the group on Scotiafjellet, a thin band of the very fine grained limestone shows small scale current bedding.

Though the 'upper' and 'lower parts' seem to conform well to the northern sequence, the central slate division, though still of slates, shows some minor differences. The lithological divisions were mapped in detail in the country between Ormondryggen and Conquerorfjellet, mainly to demonstrate the effects of composition on the formation of


FUCLEAUK
QUARTZITES
N
Black slates
and limestones
of
Upper part
BLACK
SLATES
BLACK
Black Slates and limestones
Grey Wacke
SLATES
of Lower part
CONQUEROR
GROUP
SCOTIADALIAN
0
MILES
1

chloritoid. However, they are of interest also from the stratigraphical point of view, since they almost certainly indicate a change in facies from the simple black slates of the north. Diagram 9 illustrates the distribution of the divisions. The total thickness of the central part of the group in the south is 1800 ft.

Slides of members of the group are numbers :-
310B, 313, 347B, 353, 354, 418, 419, 447, 460, 462, 963, 974, 1001, 1038, 1058, 1213, 1317, 1337, 1396, 1866, 1867, 1944, 1945, 1946, 1947, 1948, 1949, 1950, 1951, 1952, 1953, 1954, 1955, 1956, 1957, 1958, 1959, 1960, 1961, 1962, 1963, 1964, 1965, 1966.

THE PINKIE GROUP.

This group occurs in a small area on map B, west of Rudmosefjellet, thrust into the core of the Charles anticline (profiles B4 to 7). Its relation to the other groups is not known. The total exposed thickness is 2950 ft. but the position of the beds, in the core of a fold, suggests that the original thickness may have been less. However, the beds below the Pinkie group are never seen and the top of the group is probably cut out here by thrusting.

The succession developed on Veslefingeren is as follows:-

OVERTHRUST CONQUEROR AND BARENTS GROUPS.

5. 760ft. grey quartzose silts, weathering brown: more quartzitic in the upper parts: one thin conglomerate band, - 70ft. from the base.
4. 80ft. light grey quartzite.
3. 480ft. dark grey siltstones and black silty slates, weathering grey.

2. 120ft. fine grey quartzites weathering brown; and one thin conglomerate band.
1. 1500ft. light to very dark grey siltstones, occasionally more quartzitic; they weather brown.
BASE NOT SEEN.

Thin sections show that some of the siltstones are calcareous, and occasionally oval blebs of carbonate, about 2 cms. long, are 'sweated out' from the surrounding rocks, Slides 1373 and 1375 are typical of the siltstones. Recrystallisation has destroyed all original sedimentary textures (apart from bedding). 1375 shows carbonate replacing quartz extensively. Both contain fairly large amounts of argillaceous material(about 30%): of the rest carbonate makes up 8% of the rock in 1373, over 40% in 1375.

On the spur, south-west of Boureefjellet, at a height of 1430ft., occurs a lens of quartz-magnetite schist about 20ft. thick, below which lie 60ft. of green-grey phyllites and smashed black slates. These are separated from the main outcrop of the Pinkie group by a thick formation of slate breccias, taken to be part of the Scotia group cataclastically deformed and thrust out of normal sequence.

The quartz-magnetite schist and associated rocks are thus not likely to be part of the Pinkie group, nor can they be ascribed to any other group: this is however, a convenient place to mention them.

Thin sections 1366, 1367, 1368, 1389, 1370 and 1371 were made in the hope of discovering the origin of the quartz-magnetite schist. The associated rocks show little of interest- only a minor amount of metasomatic replacement is seen locally in specimens just below the magnetite horizon. The latter in section is seen to be much recrystallised it is composed of 40% quartz and nearly 60% magnetite with a little siderite (2%) and argillaceous matter (2%).

It seems likely that it is the product of metamorphism of an unusually iron rich sediment, but it is impossible to come to any more specific conclusions.

THE LARSEN GROUP.

Thrust within the core of the Charles anticline in the region of Magdabreen and Alfredbreen, are a series of rocks whose relation to other groups is unknown. The sequence in itself is evidently much distorted, and further complications arise from the fact that the rocks lie partly within the belt of Tertiary faulting.

No very coherent succession can be made out. On 'Backbiter' a series of dark fine grained lime mudstones and black slates, lithologically identical to the rocks of the Scotia group, occur in the core of the anticline (profile C8). The thickness is over 600ft. Another lens of these rocks occurs on the ridge making the west wall of Alfredbreen; they presumably follow the upper limb of

the anticline eastwards from the ridge - in mid-air as it were - to be brought down to present topography in the down-faulted Tertiary belt of Sesshogda. They run as a formation about 400ft. to 450ft. thick across the belt of faulting in the position shewn by the dotted lines in profile C6. The beds are almost certainly part of the Scotia group, out of position as a result of thrusting. Further north, the Scotia group certainly occurs in an exactly similar structural position, (profiles B11 to 13), but the various rocks here apparently associated with them do not. The identification is not quite certain and it has been thought wiser to consider together <u>all</u> the allochthonous rocks in the core of the anticline in this Alfredbreen-Magdabreen area, and mark them simply as one group on the map.

East of the Scotia-type rocks in the core of the fold of Alfred Larsentoppen lie a series of 500ft. of black slates, 180ft. purple slates, 400ft. very fissile green slates, 200ft. silty green-grey slates, followed by 1600ft. of silty slates, brown and black in colour, mostly weathering brown towards the lower part, black slates are more prominent.

Within the belt of faulting on Geddesfjellet occur similar black slates, some green slates, compact green silty quartzites, and finely banded siltstones, dark grey and brown.

Because of the confusion within this rather artificial 'group', and its allochthonous position - isolated from the coherent succession of the main groups - no thin sections have been studied.

SOUTHERN DIVISION

THE GORDON GROUP.

Rocks of this group are structurally the lowest seen in the southern range area, outcropping only south of the fault through the valley north of Hannayfjellet, in the core of the great southern anticline. The rocks occur as a strip along the coastal exposures of Brucebukta, and on the lowest parts of the ridges stretching far out to the east from the southern range. (Maps C and D)

The base of the group is never seen; the maximum observed thickness is 3300 ft. in the area east of Hardiefjellet. The Geikiebreane and the raised beach deposits prevent the measurement of continuous sections.

At the top of the group east of Hannayfjellet are 100 ft. of very pale grey, compact crystalline limestones, weathering a darker grey where nearly pure, or a slightly brownish buff in bands where the silica content is greater. Differential weathering leaves the quartz grains protruding on the surface and gives a gritty texture; thin siliceous laminae thus stand out and indicate bedding.

In thin sections 8801 and 8801i, the composition is seen to be quartz 10%, plagioclase 10%, dolomite 80%. In

the recrystallised matrix of dolomite the crystals now vary from 0.7 to 1.2 mm. in diameter, enclosing rounded detrital grains, of an average diameter of 0.4 mm., though some are as much as 1.3 mm. The larger ones are of pre-existing quartzite - each fragment consisting of several quartzite grains showing strong 'strain-polarisation' under crossed nicols: smaller grains are of quartzite often strained, and of detrital plagioclase; the quartz and some of the plagioclase show many small inclusions.

No argillaceous material, or iron ore, is present. Slide 879 is rather similar; here the mainly dolomitic matrix again makes 80% of the rock, but there are many small grains of 0.3 to 0.4 mm. in diameter in addition to the larger recrystallised grains, of 1 mm. or more. These small carbonate grains may be detrital. The rest of the rock (20%) is almost exclusively quartz - more irregular grains than in slide 880, averaging 0.3 to 0.4 mm. across. There are only one or two detrital grains of plagioclase.

Below these limestones are a series of at least 400 ft. of calcareous phyllites and silts - some black and lustrous, weathering dark brown, but mostly light or medium grey, weathering to a browny-grey. They are frequently pyritic.

The raised beaches cover the rest of the succession

except for the coastal exposures which represent horizons about 600 ft. below the top of the series. Here is an apparently thick series of dark grey - almost black - silty limestones (very often pyritic): in part they have recrystallised and are veined by calcite. Surfaces weather white, or a light dusty brown.

Very similar rocks are seen at Gordonpynten, that is about 3800 ft. stratigraphically below the top of the group. They are lost below the raised beaches south of this point, but the calcareous and silty phyllites above them outcrop on the lower slopes of the 1300 ft. hill 1·4 miles south of Gordonpynten and are surmounted higher up by the limestones of the top of the group, here again about 100 ft. thick.

THE GEIKIE GROUP.

Lying above the Gordon group, this series of rocks crops out on the eastern ridges of Hannayfjellet and Neukpiggen, and also in the strip of country south of Geikiebreane. The group becomes considerably thinner towards the southern end of the outcrop, being only 1440 ft. thick on the hill, 1300 ft. high, SE of Hardiefjellet. The maximum thickness of the group is 3,800 ft. reached on the ease ridge of Neukpiggen, but the junction with the

Ferrier group above is complicated by faulting. Details of the upper part are therefore taken from observations on the east ridge of Hannayfjellet.

The group consists essentially of monotonous alternations of two rock types - calcareous schists, and limestones proper. The lowest 100 ft. is composed largely of banded slabby grey schists, with a high carbonate content, in which are a few bands of limestone - light grey, siliceous, with a little mica: the siliceous bands weather out differentially to indicate bedding. There follow 1200 ft. of fissile calcareous schists and slabby schists, more siliceous, but still with a carbonate content of about 10%. A sequence of grey, gritty limestones follows, about 380 ft. thick, in which are seen occasional thin bands of calcareous schists. In the following 850 ft., calcareous schists and limestones alternate, the latter becoming dominant in the upper part. The highest 1300 ft. of the group again consists of alternating limestone and schist zones but the average thickness of each - about 30 ft. - is rather greater here than lower in the sequence.

Slide 760 is typical of the calcareous schists - being composed of 40% carbonate, 40% quartz and 20% mica. Little of the sedimentary texture remains. Slide 877, of the dark

grey limestone, shows 10% quartz and 90% calcite; with very little micaceous material. Layers of a fine dust of iron ore, probably pyrite, delineate the bedding. Thin section 780 is typical of the more quartzose schists: quartz makes 70% of the rock; mica 20%; carbonate about 10%.

Of the whole succession, about one third is composed of limestone.

THE FERRIER GROUP.

The rocks of this group, covering a large area of the southern range, are largely fissile grey calcareous phyllites with subordinate slabby, calcareous quartz schists, pale brown or grey. Essentially they represent a very incompetent series of rocks which are strongly affected by small scale folding and thrusting. This fact and the small range of variation in lithology, make it quite impossible either to subdivide the group into parts, or to estimate accurately its true thickness. The apparent thickness, ignoring repetitions by folding and thrusting, reaches a maximum of 4,450 ft. in the region of Doddsfjellet: the top of the group is never seen. As well as the main rock types mentioned above (calcareous phyllites and calcareous

quartz schists), there are occasional bands of quartzites and black phyllites, with little or no carbonate material; very rarely there occur siliceous limestones.

Thin sections of members of the group are numbers 788, 794, 795, 820, 821, 1478. Recrystallisation and shearing have destroyed original textures and made it impossible to assess grain sizes. Slides 821 and 1478 are characteristic of the papery calcareous schists - with 50% quartz, 30% carbonate, 20% mica in one slide, and 50% quartz, 45% carbonate, 5% mica in the other. Plagioclase, schorlite and magnetite are accessories. Slide 820 is of the slabby, more quartzose schist which makes up about one quarter to one third of the succession: quartz 80%, dolomite (altering to siderite) 12%, biotite 8%. Slide 795 is one of the less usual rocks in which the carbonate content falls to about 5%; quartz makes up 55%, mica 40%. Slide 778 represents a typical quartzite - and shows less recrystallisation than in most specimens: grains of quartz, averaging 0.2 mm. in diameter, constitute over 90% of the rock, interstitial carbonate grains, slightly smaller than the quartz grains account for 5%: mica makes up a little over 1%, and albite and schorlite are present as accessories.

THE ISACHSEN GROUP.

This is the group of rocks which lies between the two great thrust planes of the southern range. Their outcrop runs as a strip from Scotiadalen to Methuenfjellet. The series of epidiorites shown on maps C and D lie parallel to the bedding and serve to indicate at a glance the way in which the thrusts cut across the sequence of the group. Thus, the lowest beds are seen in the valley between Hannayfjellet and Johansenfjellet: the highest are seen on the south side of Scotiadalen. The apparent thickness of the group is 4,400 ft. but there is likely to be some repetition by thrusting, so that this figure may be larger than the true thickness.

The lithology is very uniform throughout. The dominant rock-type, making up about four fifths of the succession, is a semi-pelitic schist (slabby or friable according to the amount of pelitic material) with about 10% of carbonate material. The rock weathers to a very characteristic light brown.

Slides 1490 and 1494 from Hardiefjellet are typical of these rocks; recrystallisation has, of course, destroyed all original sedimentary textures, but the composition is seen to be 60% quartz, 30% pelitic material and from 5%

to 10% carbonate. As accessories there are small amounts of magnetite (greatly decayed) and a little plagioclase.

Rarely, the carbonate content reaches 50%, producing slabby siliceous limestones, usually buff-white in colour; intermediate grades of calcareous semi-pelitic and calcareous siliceous rocks occur.

Almost pure limestones do occur, as occasional bands, but there is nothing approaching a pure quartzite in the series.

THE NELSON GROUP.

Above the higher of the two great thrusts of the southern range, lie two series of rocks, of which the lower constitutes the Nelson group. The base of the group is never exposed, the apparent thickness of the beds decreasing northwards from a maximum of 4,600 ft., west of 'Nelson', until they are cut out altogether by the thrust.

The rocks are a uniform series of slabby, grey, thinly-banded silts and semi-pelitic rocks, mostly with a small amount of carbonate material. The latter component has in places 'separated out' during metamorphism into oval blebs and patches. These rocks form the great slabs which comprise the steep western faces of the mountains.

Occasional slabby quartzite bands occur - these are grey, never pure.

The lowest part of the succession is seen in the wedge shaped area lettered N' in Map D. The lithology is similar to that of the rest of the series but there is an unusual formation of very fissile black slates, 120 ft. thick, along the top of which has been mapped the line of demarcation between N' and the rest of the group. Stratigraphically this division is not particularly significant; the line was mapped to indicate clearly the way in which the thrust cuts across the beds of the Nelson group.

THE KERR GROUP.

To the west of the mountains of the southern range, underlying the raised beaches of the plain, Peachflya, and outcropping along the west coast southward from Kerrlaguna, is a very thick series of rocks which make up the Kerr group. They are poorly exposed in the raised beach area, though partial traverses can be made across the strike at several places.

The thickness of the group apparently exceeds 7,300 ft., calculated from the average dip of 75° W. and the width of the outcrop (not including the width of ~~the~~ Kerrlaguna itself

where there are no exposures). The 'highest' (i.e. westernmost) part of the sequence outcrops along the coast west of Peachflya - a series of black slates, brown weathering; dark grey limey silts, weathering brown; occasional pyritic dark quartzites; and a mass of grey and green phyllites in which chloritoid develops abundantly.

Further inland, about five or six hundred feet lower in the succession, are further dark quartzites and dark, limey, quartzose silts. After a gap of 4000 ft. the lowermost 1900 ft. of the succession is seen to consist of black and dark grey slates - brown weathering; green and grey phyllites - often silty; dark grey, fine-grained, slabby quartzose silts, brown weathering; and occasional bands of grey quartzite, and grey siliceous limestones which weather light brown.

Near the base of the group west of Hardiefjellet are fine-grained lime mudstones (slightly siliceous) and some very pyritic black limestones.

From these fragmentary descriptions it must be clear that it is not possible to give any detailed succession for the group. The rocks of Forlandsoyane and the west coast south of the fault running obliquely across the island from just north of Urmstonholmane, have been mapped as part of

the Kerr group in view of the presence in the Forlandsoyane of a thick series of green and grey phyllites similar to those of the coast west of Peachflya, and of a series of dark quartzites and slates making the islands nearer the shore. This suggested distribution is consistent with the small displacement of the fault referred to above, as seen in the well exposed mountain area.

THE PERSIS GROUP.

The precise relation of the rocks of the far south - Persiskammen and Salfjellet - to those of the southern range is still unknown. In the intervening area of raised beaches, Forlandsletta, are fewer than a score of outcrops, all of limestone too much broken up by frost to allow the attitude of bedding to be seen. Coastal exposures are very scanty.

The sequence on Persiskammen has been split into four parts lettered V1 to 4 on the map (E), V4 being the highest. The succession is as follows:-

V4	60 ft.	Black phyllites, and occasional bands of more siliceous, black, semipelitic rocks.
V3	120 ft.	Finely-banded grey siliceous limestone: more siliceous bands, generally about 1 mm. thick, weather out differentially.

V2 240 ft. Mainly dark grey quartzites, calcareous, pyritic, weathering black. In the upper part a few intercalations of light grey, finely crystalline limestones, slightly siliceous, weathering grey and white. Slide 678 is of a thinly bedded rock in which lime-rich and quartz-rich bands alternate - the proportions of these two constituents ranging from 95% quartz 5% carbonate, to 5% quartz 95% carbonate.

V1 475 ft. Dark grey mica schists, weathering brown; more quartzose in the higher part of the sequence. Thin light grey limestone bands.

Total thickness - 895 ft.

THE SALFJELLET GROUP

South of the fault which separates Persiskammen from Salfjellet is a series of rocks which must total over 9000 ft. in thickness. As well as fairly good exposures in the mountain area, it is possible to trace boundaries over the raised beach area where sharp differences in lithology are reflected in surface features. The lines delineating the parts of the group lettered Z1, Z2, Z6 and Z7 were mapped in this way; but a detailed succession within these parts of the group could not, of course, be measured.

The central section is well exposed, the sequence being as follows:-

Z5 1550 ft. Mainly grey mica schists, weathering dark grey; occasionally green bands in the lower part.

Z4 3200 ft. 40 ft. black, banded limestones, fine-grained, partly dolomitic. In thin section (687) seen to be composed of roughly 90% carbonate, 3% quartz, 6% pyrite, 1% muscovite.
150 ft. quartzose schists.
50 ft. dark grey and green mica schist, the latter silver weathering.
100 ft. quartzose schists.
30 ft. black, banded limestone, as above, the lowest 20 ft. more finely grained.
120 ft. quartzose schists and quartz schists, slabby, weathering brown.
2700 ft. thick uniform series of slabby dark grey, finely banded limestones, pyritic, with some lighter coloured bands. At 100 ft. from the top is 20 ft. of mica schist, and thin bands are also intercalated lower in the series.

Z3 900 ft. Grey impure micaceous limestones weathering a light grey, occasionally yellowish.

The relation between the rocks of the Salfjellet and Persis groups is impossible to state. The Persis sequence may well be equivalent to that part of Salfjellet group covered by beach deposits, either higher or lower than the exposed central portion detailed above.

This sequence in the far south of the island is not equivalent to any part of the succession in the southern range. Whether the beds of Persiskammen and Salfjellet are stratigraphically higher or lower than the extreme limits of

the southern range is not known. It is even possible that they represent a series of strata which are cut out in the southern range by thrusting.

RECAPITULATION

The stratigraphy may be summarised in tabular form thus:-

NORTHERN DIVISION

N4.	Scotia group	> 4,000 ft.
N3.	Conqueror group	? 4,800 ft.
N2.	Barents group	> 2,300 ft.
N1.	Fuglehuk group	> 4,000 ft.

TOTAL 15,100 ft.

Pinkie group > 2950 ft. Larsen group > 2800 ft.

TOTAL FOR NORTHERN DIVISION: > 20,800 ft.

SOUTHERN DIVISION

S3.	Ferrier group ?	>4,450 ft. - certainly > 3000ft.
S2.	Geikie group	3,800 ft.
S1.	Gordon group	>3,300 ft.

TOTAL >10,100 ft.

Kerr group	> 7,300 ft.
Nelson group	> 4,600 ft.

TOTAL >11,900 ft.

Isachsen group ? > 4,400 ft.

Persis group > 900 ft.

Salfjellet group > 9,000 ft.

Minimum thickness of Southern Division: 28,500 ft.

- taking only those parts of the successions which could

not possibly be correlated, i.e. ignoring rocks of incompletely exposed areas, such as divisions Z1, Z2, Z6 and Z7 of the Salfjellet group, and so on.

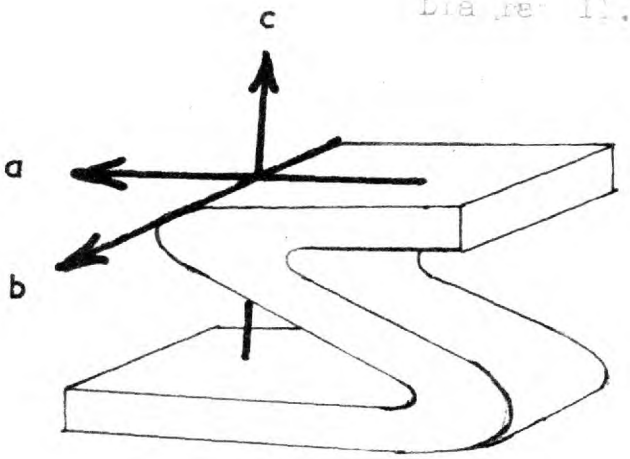
Accepting the unlikely possibility that the Larsen group, and the Kerr group are the same in part, the minimum thickness of the Hecla Hoek formation on Prince Charles Foreland is 46,500 ft.

Discussion of the stratigraphy in a regional setting is deferred to Chapter V, when the development of the Hecla Hoek formation elsewhere in Spitsbergen is reviewed.

BASIC INTRUSIONS

A series of sills was intruded into the sediments before or at a very early stage in folding and metamorphism. It would be pleasing to describe them at this point, but since they have all subsequently been intensely sheared and altered, their original state can only be inferred from a study of relict textures. The subject is therefore dealt with in Chapter IV: Metamorphism - ("The Epidiorites" - page 134)

Diagram 11.



STRUCTURE.

Diagram 10† summarises all the structural observations made in the Hecla Hoek rocks. The area of the island has been broken up into a series of sub-areas, each corresponding to a small geographical unit - a mountain, or a strip of coast. On an equal area stereographic projection all observations within each area have been plotted, that is, the attitude of linear structures, and poles of bedding planes. The heavy black line across each circle is the best approximation to an average for the distribution of the poles of bedding planes; i.e. it is the projection of the plane which is traced out by lines at right angles to the limbs of the folds, the ac plane in fact, using the letters a, b and c in the sense illustrated opposite (diagram 11).

The black circle indicates in each case the average orientation of the minor structures - drag folds, lineations, intersections of cleavage and bedding, boudinage structures, rodding. The stereograms indicate that these structures are, in each area, at right angles to the ac plane, traced out by the poles of bedding plane measurements. They are thus b-structures. The fact that the lineation - which is clearly a recrystallisation feature - follows exactly the local variations in fold trends, is definite evidence that recrystallisation and metamorphism were active as the folds developed. Were the lineation a later feature, it might be expected to run across fold structures, ignoring local variation in the

† See portfolio

direction of the fold axis.

The maps A-F, simplified and correlated versions of the field-maps are rather difficult to read, until one is used to thinking in terms of vertical relief and flat-limbed recumbent structures, rather than of open structures, with relief not playing a crucial part in the form of the geological map. This obvious and inevitable difficulty has prompted the presentation of the main bulk of the structural results, in the form of a series of cross-sections (profiles A1 to E2). The relief is so strong that there has been no need to exaggerate the vertical scale. The sections have been drawn at the same scale as the maps A to E, so that thicknesses and other measurements can be read off directly. To obtain a true profile of the folds, each section has been drawn at right angles to the local b- direction, ie. parallel to the heavy black lines of the stereograms - the a/c planes. The lines of the sections are shewn on diagram 12, being taken usually through summits and the prominent W and E ridges of mountains. The best topographic line for a section does not usually correspond exactly to the ac direction determined statistically from the structural observations. In all these cases, the section has been projected onto a plane of the required orientation. The angle involved is rarely more than 15°.

For a true profile the plunge of the structure must, of course be taken into account, In 34 of the sub-areas the plunge is zero, in only 4 is it as much as 10°. For the rest it is about 5°. It has not been considered necessary to project the vertical sections onto planes dipping at 85° and so on, as the maximum distortion involved in a 5° error in orientation is a factor of only secant 5° - an exaggeration of 4½ inches for a bed 100ft. thick. (At 10° the corresponding error is only 1.5ft.). Over a section 3,000ft. in height, the distortation is just over 11ft., - at this scale impossible to plot.

The sections, therefore, are all vertical, and are true profiles - ie. views of the structure looking along its plunge-direction. In large measure they are self explanatory. Section A1 is the reverse projection of the view of the Fuglehukfjellet recumbent fold, discovered in 1950 - (plate 15). Green slates of the Barents group appear in the core of the fold, forming an isolated oblong outcrop west of the summit - see maps A and F.

Section A2 runs across the island two thirds of a mile further south and crosses the Tertiary graben before reaching the coast. The conspicuous vertical fault 1,000ft.E. of the highest point in the section is parallel to a marked system of Hecla Hoek faulting - see map F ; but the anticlinal warping it cuts, and the large displacement of about 700ft. are almost certainly Tertiary effects. The block is

downfaulted (along three faults, running E-W, N-S, and NE/SW) in sympathy with the downward movement on the main Tertiary graben fault. Whether or not the anticlinal structure is also a Tertiary effect similar to Tertiary structures appearing further South - the faults running across the island between the sites of section A2 and Section A1 must have large lateral (sinistral) displacements, since there is no sign of the steepening and overturning of the beds seen on the E. face of Fuglehukfjellet. On the contrary the beds are right way up as far E. as the graben fault, and a few doubtful exposures on the coast just NW of the fault suggest that the eastward dip has brought green quartzites of the Barents group down to sea level at this point.

Section A3 is nearly a mile south of A2. The lowest beds of the Barents group outcrop as a thin veneer on the dip slope of the S.W. face, isolated from the main belt. The highest division of the Barents group is cut out, for the overlying beds are thrust onto the central formation of the group. The total thickness of the Barents Group is only 1,200ft. at the coast.

This thickness increases rapidly as the overthrust is followed eastwards onto the northern part of Barentsfjellet. But the apparent thickness (ie. the distance between the beds of the Fuglehuk group below, and the Conqueror group above) is further increased by intensive small scale isoclinal folding of the incompetent slates of the Barents group,

flowing between the two great quartzite series. The displacement on the thrust was evidently contemporaneous with the main fold movements, and produced the violent overfolding shown in the section, A4. The folds on the N.E. ridge of Barentsfjellet run in a direction almost at right angles to the axis of the recumbent fold of Funglehukfjellet. In 1950 when the northern area was the only part of the island that had been mapped, this posed a considerable structural problem. The area was re-mapped at double the scale (map F), partly to resolve this question, and partly in order to arrive at a sound, detailed stratigraphic scheme in this area where metamorphic grade is low. The tear faulting which displaces the Fuglehukfjellet axis to a position far E. of Barentsfjellet, was then discovered, and the gradual swing in the structural trend was mapped (see Map F, and diagram 10). Considerable variation in trend of folding was found further south - as is shown in diagram 10 , but it is nowhere so pronounced as in this area in the north.

In the Conqueror group above the thrust a set of symmetrical undulations has developed. These were mapped along the coastal exposures (Map F) but were not observed on Barentsfjellet. They plunge fairly consistently to the S.W., at an angle of about 30°. Developing at right angles to the main movement direction, they are probably the result of slight lateral convergence and shortening, accompanying the advance of the overthrust rocks.

Rocks of the Scotia group are first encountered in the small hill south of Barentsfjellet, where they form a synclinal infold in the Conqueror group. The presence of the characteristic facies of the junction of the Conqueror and Scotia groups indicates that here there is no important structural discordance.

The rest of the great synclinorium of the southern part of Map A shows several further minor anticlines and synclines. The large syncline of the centre of Taylorfjellet has in its core a series of black slates, 500ft. thick. The plunge of this structure coincides with the direction and angle of the ridge running down south-eastward from the summit, to Svarthaugen, in such a way that the infold of slates runs as a belt of almost constant width, across and down the mountain.

Niggdalen is the site of an anticline, through which an important fault cuts, with a downthrow to the south of considerable magnitude. The presence of quartzites of the Conqueror group on the coast 1,000ft. north of the exit of the stream from Niggdalen, indicates that the base of the Scotia group cannot be far below sea level under Nigghaugen, but on the other side of the fault, from the geometry of the section, it is clear that the base of the group must be at least 2,000ft. below sea level and probably more. The three faults through Nigghaugen have a similar direction of displacement - downthrow to the south - though of much

smaller magnitude. The fault just south of the summit of Taylorfjellet, has a small displacement in the opposite sense, but the two faults north of the mountain again show downthrows to the south. The one in the valley has a displacement of about 400ft., the one a little further south is apparently a hinge fault, with a downthrow of 200ft. on the east face of the mountain, over 400ft. on the west face.

The northern part of Stairhogdene is the site of an asymetrical syncline, the beds of the south-west limb undulating near a vertical attitude. Beds of the Conqueror group appear half way between the north summit of Stairhogdene and Nordre Sutorfjellet, vertical ribs of quartzite on the northwest face folding over in an asymetrical anticline in such a way that the top of the group just fails to reach the ridge. The fault, which cuts through the vertical limb just north of the junction of the Scotia and Conqueror groups, is evidently not quite parallel to the plunge of the structure for on the southeast face it is seen that the vertical Scotia beds abut against flat lying Conqueror quartzites of the southwestern, flat limb of the anticline. The downthrow is to the north-east, but the actual displacement of the fault is difficult to estimate since the beds it cuts are mostly parallel to it, that is almost vertical.

The problematical conglomerate of the Sutorfjella appears just west of the anticline. Detailed mapping showed

that a whole series of rocks is involved in this area - green slates and quartzites in addition to the more conspicuous conglomerate. On Sore Sutorfjellet the beds were found to be folded into an asymetrical anticline, and the stereographic diagram for observations in these rocks - (shewn on diagram 10) clearly indicates that they have a structural unity with the Hecla Hoek formation, and are not an undeformed later deposit as was thought by previous authors (see p. 21). On Nordre Sutorfjellet the conglomerate lies above fine green slates, and dips rather north of west at an angle of about 25° or 30°. The exposed thickness is about 250ft., the top of the conglomerate lying an unknown distance beyond the coast. On Sore Sutorfjellet the rocks are folded into an asymmetrical anticline, the nearly vertical limb extending from 250ft. to about 400ft. below the summit where the dip lessens to 20° to the northeast. At the base of the mountain also the dip lessens to 10° NE, as the flat limb of the complementary syncline comes in. Section A5 illustrates these remarks: the conglomerate is seen to be at least 400ft. thick here, though as on Nordre Sutorfjellet the top is not exposed. The beds below are characteristic green and orange weathering slates of the Barents group, and it is plain that the problematical Sutor rocks, are in fact part of the Barents group of the Hecla Hoek formation. The flat-lying limb of the syncline underlies the rest of the low ground around Sore

Sutorfjella as far north as the fault which runs across the island through Mackenziedalen: minor faults running at 45° to this latter fault, displace the conglomerate in a westerly direction on their north sides. They have the appearance of tear faults but the displacement may as easily be explained by small downthrows to the north since the beds affected are almost horizontal and a slight vertical displacement would cause a considerable shift in outcrop at the surface. The flat S.W. limb of the Sore Sutorfjellet anticline is never seen since it would fall to sea level well beyond the coast. It is however, lowered by the Mackenziedalen fault, and represented by the triangular area of the Nordre Sutorfjellet block. The Sutor anticline is presumably the up-faulted core of the anticline seen in the Conqueror group E. of the faults which separate the Sutorfjella from Stairhogdene and St.Andreashaugane. This set of faults inclined at about 70° to the south-west, and therefore reverse faults, must have a very considerable throw.

Faulting has made this small area at the western end of section A5 appear extremely complicated. The rest of the profile is straightforward, The large asymmetrical syncline of Stairhogdene is raised on the south side of the Mackenziedalen fault to such an extent that on the southern side of St.Andreashaugane, the base of the Scotia group never falls lower than 500ft. above sea level. The plunge of the structure however is about 10° to the N.W.,

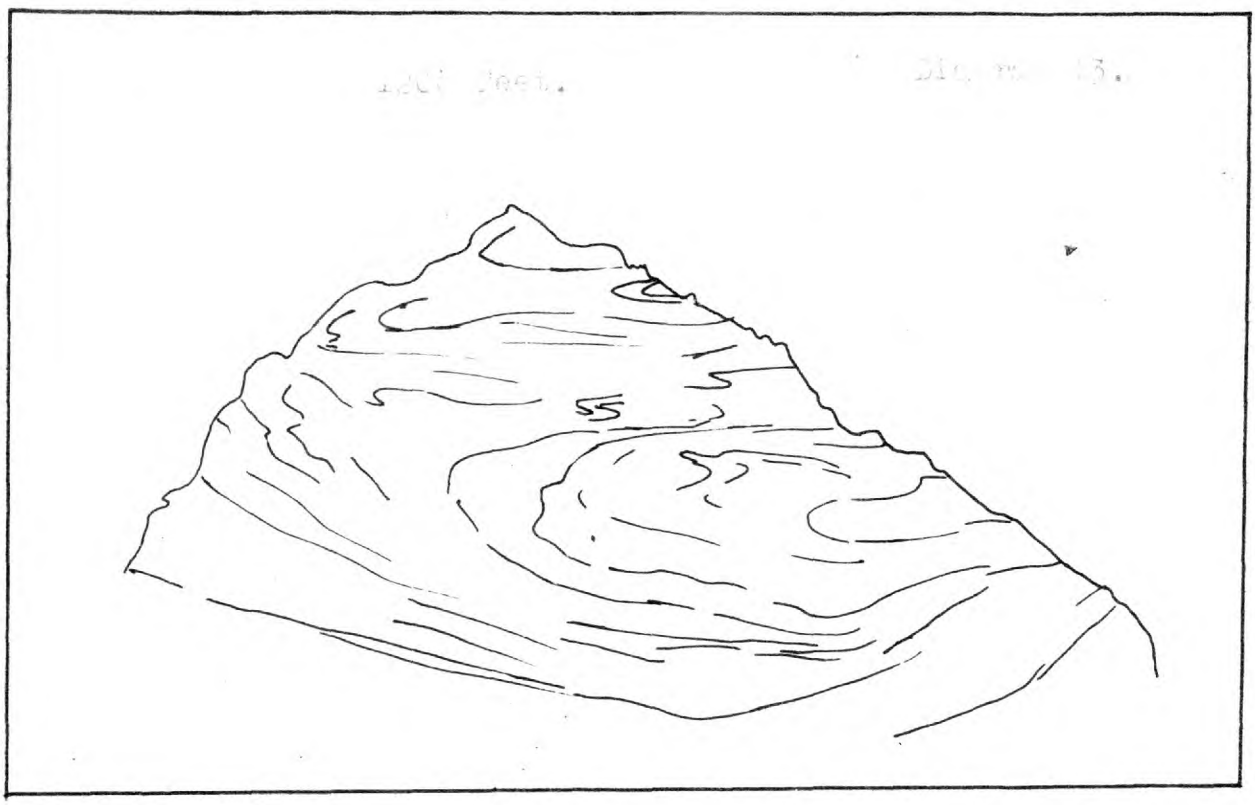
so that at the section line (through the centre of the mountain) thejunction reaches just below sea level. The throw of the Mackenziedalen fault must be of the order of 1,500ft. or more down to the north, judging by the displacement of the syncline. This is quite sufficient explanation for the apparently curious way in which the two limbs of the Sutor anticline are disposed on either side of the fault. The north-south reverse faults were evidently earlier than the Mackenziedalen fault.

The fault running through the valley south of St. Andreahaugane again has a downthrow to the north. The great syncline of Stairhogdene and St.Andreashaugane has much the same shape in profile B1 (Leefjellet) as further north, but on Hellandfjellet the structure is distinctly tighter - profile B2. In section B3 above the Conqueror group quartzites lies an overthrust wedge of Scotia rocks, cut out to the west by a further overthrust mass of Conqueror beds. As will later be seen, this latter overthrust block is actually the highest structural element on the Foreland. The overthrust must continue north of the west end of Laurontzfjellet, and may run through the raised beach area, somewhere between Hellandfjellet and the coast. It would be extremely difficult to detect, since there are only a few frost shattered outcrops, and the beds on each side of the dislocation are of similar lithology and have approximately the same dip.

The lower thrust of profiles B1, B2 and B3, brings rocks of the Scotia group in contact with part of the Barents group, and in beds of suitable composition, chloritoid is produced as a result of the unusually strong movement and stress. This association of the development of chloritoid with thrusts and belts of sliding is almost universal in the Foreland occurrences of the mineral. (The question is deferred to the section on metamorphism, but the structural evidence is given here as part of the general tectonic description).

Profiles B2 and B3 shew clearly that the Conqueror group is sliding over the Barents group. The deformation of the latter has been too strong to allow the various formations seen on Barentsfjellet to be distinguished here. In the area E. of Leefjellet and Hellandfjellet the thickness is not known since the beds appear only in the centre of two anticlines, the rocks below never reaching the surface. But on the south side of Laurontzonfjellet the whole Barents group in places totals only 200ft. in thickness. Just west of the central fault of profile B4 chloritoid is again found in the Barents beds.

On the two sides of Millerbreen, the Fuglehukfjellet quartzites are seen to be intensely overfolded above a major thrust plane: the rocks below - slates and quartzites of the Conqueror group are greatly sheared and shattered. Drag



folds above and below the dislocation indicate a westward direction of overthrusting. The thrusts of the eastern parts of sections B1 and B2, also have a westward direction of movement, shewn by numerous drag folds, and even more strikingly by the large scale overfold in the Conqueror group, seen underneath the lower of the two thrusts in section B3.

The Upper Structural Unit.

In the central and southern parts of Map B, it becomes very clear that the large structural unit so far discussed, overrides the rocks below with complete discordance. The Fuglehukfjellet quartzites which form the upper part of the Rudmosefjellet group of peaks, and of Monacofjellet and Parnasset, are outlying 'Klippe', the higher peaks reaching up into the lower levels of the overthrust unit - see profiles B5 to C2. On the north and south faces of Rudmosefjellet, there are huge cliff sections in the Fuglehuk quartzites - showing impressive recumbent overfolding to the west (profiles B6, B7, and diagram 13).

A zone of mechanically mixed rocks is developed below the thrust here, lenses of brecciated siliceous limestone of the Barents group 'floating' in brecciated, and sometimes mylonised rocks of the Conqueror group. The zone has been shewn on the Map B , since it is locally almost 400ft. thick. Within it, there is an intensely sheared lens of epidiorite

(see Map B, and Section B6). The downfaulted block of west Parnasset (profile B.13) again shows magnificent westward overfolds: the overthrust block here, and on Rudmosefjellet is moving forward on a truncated recumbent anticline. The distribution of this upper structural unit is summarised in diagram 14 as Unit 3. (Units 1 and 2 are the overthrust wedges of Scotia and Conqueror rocks in the regions of Leefjellet, Hellandfjellet, and Laurontzonfjellet).

~~Mentioned earlier~~, The upper Unit (Unit 3) has an unusual structure, for at both its east and west ends it is folded toward the centre. This can easilt be seen if the recumbent fold of profile A1 is placed in imagination at the eastern end of profile A4. This recumbent syncline of Fuglehukfjellet is orthodox in that it is overturned to the west, in conformity with the general movement. But the Fuglehukfjellet fold and the folds of north east Barentsfjellet with their flat axial planes give way further south to open folds whose axial planes are more and more steeply inclined to the north-east. On Taylorfjellet the axial plane of the syncline is vertical, and further south-west the axial planes dip to the south-west at progressively smaller angles. At the eastern end of the section (A4) the axial plane of the Sutorfjella anticline is inclined at 50° to the south-west. This asymmetrical anticline of the western part of sections A4, A5 and B1, is thus a backfold, opposed in its attitude to the general westward movement.

Its cause is obscure. It may be postulated that the advancing mass encountered some resistance, which produced an anticline in opposition to the general westward movement.



Plate 24. Unit 4. The Charles anticline, on Charles Fjellet, viewed from the north.

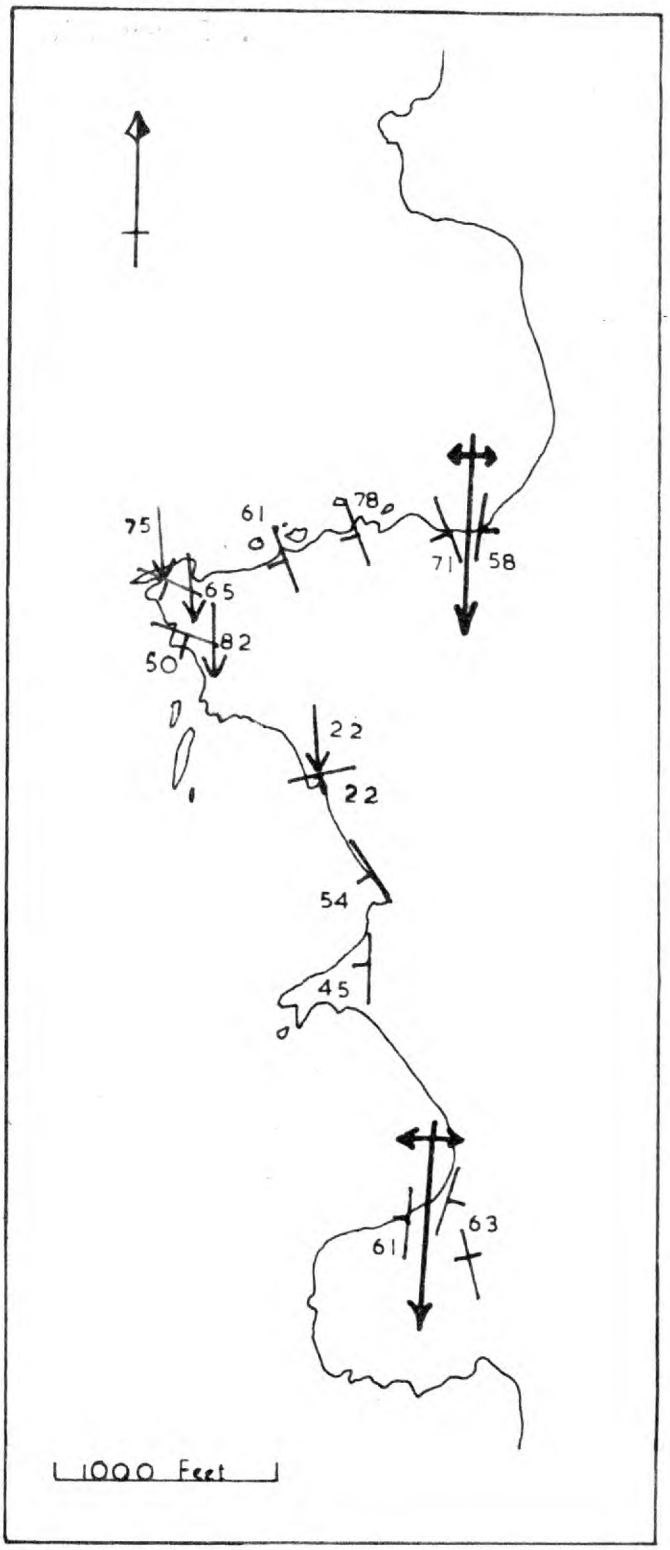
Unit 4.

The great thrust at the base of structural unit 3 rests upon the upper limb of a recumbent anticline which stretches - as maps B and C, and profiles B5 to C11 shew - for at least 16 miles, from Omondbyggen as far north as Millerbreen. Further north, rocks of unit 4 fail to reach the surface. This persistent anticline is least distorted in profile C1 (Charlesfjellet) and will therefore be referred to as the Charles anticline. In this profile (C1) the massive Fuglehuk quartzites form the core of the fold: above and outside them are the rocks of the Barents group - here attenuated to a thickness of only 250 to 300 ft. Outside this group,-that is stratigraphically above, lies the Conqueror group - its slates and quartzites much brecciated. The stratigraphical order is thus in the main undisturbed, though the Barents group is represented only by brecciated siliceous limestones, in the western part of the anticline. In most of the other sections it is clearly seen how greatly this horizon has facilitated sliding, several different formations lying thrust within the core of the Charles anticline in various localities: in the north the Pinkie group and the Scotia group; in the

centre, the Scotia group and a wedge of rocks of the Conqueror group; in the south, the Kerr group, and what is probably part of the Scotia group (see page 66). This plane of movement may well have been a thrust initiated before the main folding began. The syncline below the Charles anticline is seen in profiles B9 to C2, but it is of much smaller amplitude than the anticline, and even more variable in profile. On the west side of the range it is clear that the anticline advanced on a series of thrust-planes, the three major thrusts developed in the central range being shewn in profiles B8 to B12. A wedge of Scotia rocks lies thrust over rocks of the Conqueror group which show a recumbent synclinal structure (profile B9). This overrides and truncates a lower thrust which carries Conqueror rocks onto a group of granulated pyroxenites (discussed later, in Chapter IV).

These three great thrusts on which the Charles anticline advanced, are downfaulted to below sea level south of Phippsfjellet, and it is not until just south of Dyerlaguna that the base of structural unit 4 is seen again.

On Omondryggen the inverted Scotia group is thrust over Fuglehuk quartzites which are right way up - (profile C11). The wedges of Scotiafjellet and Conquerorfjellet rocks seen in the central range have disappeared.


75
61
78
71
58
65
82
50
22
22
54
45
61
63
1000 Feet

North of Omondryggen, however, the anticlines and synclines developed in the Fuglehuken group die out, and the beds below the thrust gradually become involved in the fold of the recumbent anticline. Profiles C7 to C11 illustrate the progressive development of this situation, the mechanics of which are not clear.

The crucial area, between west Omondryggen and a point west of Conquerorfjellet, is not very well exposed. Swings of strike to an east-west attitude can be seen in places, and on the coast west of Gourlayfjellet this phenomenon is well displayed. It is produced by a sudden plunging of the main fold axis into a vertical attitude - the axis being itself folded about a secondary east-west axis. The area around the prominent cape 1½ miles west of Gourlayfjellet is shewn in diagram 15 , and the accompanying stereographic projection shews the orientation of b-structures - drag folds and lineations produced by the general folding running north and south. They have clearly been folded about an axis running 30° S. of W., and N. of E., and in places this axis is actually represented by a fine lineation. An orientated specimen was taken from a locality of double lineations and the petrofabric diagram (diagram 16) shews that each lineation is at right angles

1922


N
FIRST GIRDLE
SECOND GIRDLE
B_2
B_1
B_2
4
2
2
0
5
3
3
1
3
1
1
5
1
2
2
0
2
2
2
2
1
2
2
1

Max. 5%

to a quartz girdle. The fact that neither girdle is broken down suggests that the two foldings were part of the same episode.

It is concluded that the phenomenon described above probably represents the mechanism by which the anticlinal and synclinal structure of Omondryggen becomes converted to the simpler structure shown, for example in profile C7.

Cataclastic Effects.

The Scotia group and the Conqueror group, are often intensely brecciated in structural units4 and 5: The siliceous limestone (B3) of the Barents group is brecciated throughout the central range. In addition to the brecciation below the advancing anticline ~~in~~ there, some of the rocks forming the anticline itself shew strong brecciation, clearly not related to thrusting, but to the violence of the folding. The Barents limestone has already been mentioned as being brecciated almost throughout unit 4, the rocks of the Conqueror group, frequently shew strong brecciation, in their normal position above the Barents group, and wherever they are seen thrust into the core of the anticline. The Scotia group is intensely brecciated in the core of the anticline, but in the complementary syncline - for example on west Buchananryggen - the deformation has not been so strong as to produce brecciation. The various



Plate 26. The Devil's Thumb (left), and Monacofje Jet.
(View south from Veslefingeren).

rocks mentioned only rarely shew signs of any further folding after brecciation. It is considered that the breakdown was produced at a late stage in the tectonic history, as a result of final violent movements of the Charles anticline; the metamorphic history supports this hypothesis (page 119-).

Brecciation has little altered the appearance of the rocks of the Conqueror group. The thin limestones and slates of the Scotia group, however, have been converted into a rock consisting of slate fragments (usually less than 1 or 2 cm.long), which are cemented by calcite. This is an extraordinarily durable rock which gives rise to unusually precipitous scenery - The 'Devil's Thumb' is largely constructed from brecciated calcareous slate - in strong contrast to the scree covered slopes of Scotiafjellet. The rock weathers with a distinctive knobbly surface. The brecciation has involved a complete rearrangement of the rock, mechanically controlled. The carbonate of the thin, fine-grained black limestones has been redistributed throughout the rock as the matrix which cements the slate fragments together. Original limestone-free bands form slate breccias without a carbonate cement.

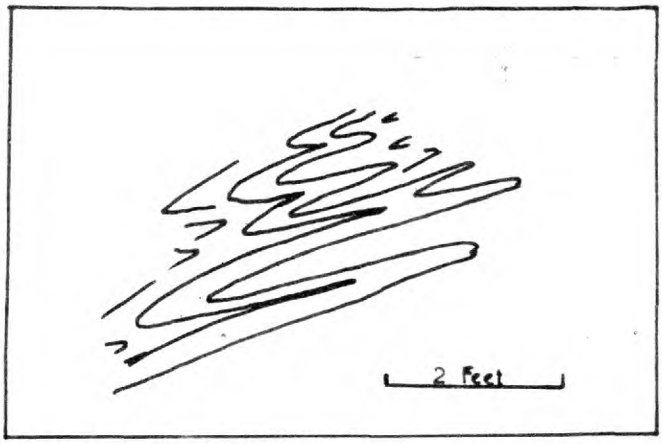
The siliceous limestone breccia of the Barents group

shows many similar features - a knobbly texture, with fragments of siliceous limestone floating in, or cemented by, a recrystallised carbonate matrix. The rock is buff, sometimes with a pale green tinge. South of Jessiefjellet it is seen to be progressively less altered until, on Conquerorfjellet, it is little changed from its original condition as a green, slabby siliceous limestone.

The Southern Range : Unit 6.

The structural feature of the southern range which is most immediately obvious is the great southern anticline, whose axis runs north and south roughly through Geikiebreane. The beds on the east coast dip eastwards at about 50°; in the mountains the dip to the west becomes progressively greater farther west until, on the coast the beds are vertical. Detailed mapping, however, soon reveals two major thrust-planes, which are folded by the anticline, and are thus clearly earlier in date. Minor structures associated with this thrusting are found to be superimposed on even earlier structures.

The first formed structures are small recumbent folds which are of flowing outline, and are accompanied by well developed lineation and drag folding. This north-south


2 Feet

folding was clearly contemporaneous with metamorphism. The orientation of the minor structures is shown in part 1 of diagram 17 (in ~~cover pocket~~ portfolio). The central part of the area is a plunge culmination - the plunges reaching a value between 10° and 20° on either side of the wide area of nearly horizontal readings. The beds are largely incompetent and no major recumbent folds appear to have formed, though the effects of the later thrusts make it difficult to be certain on this point.

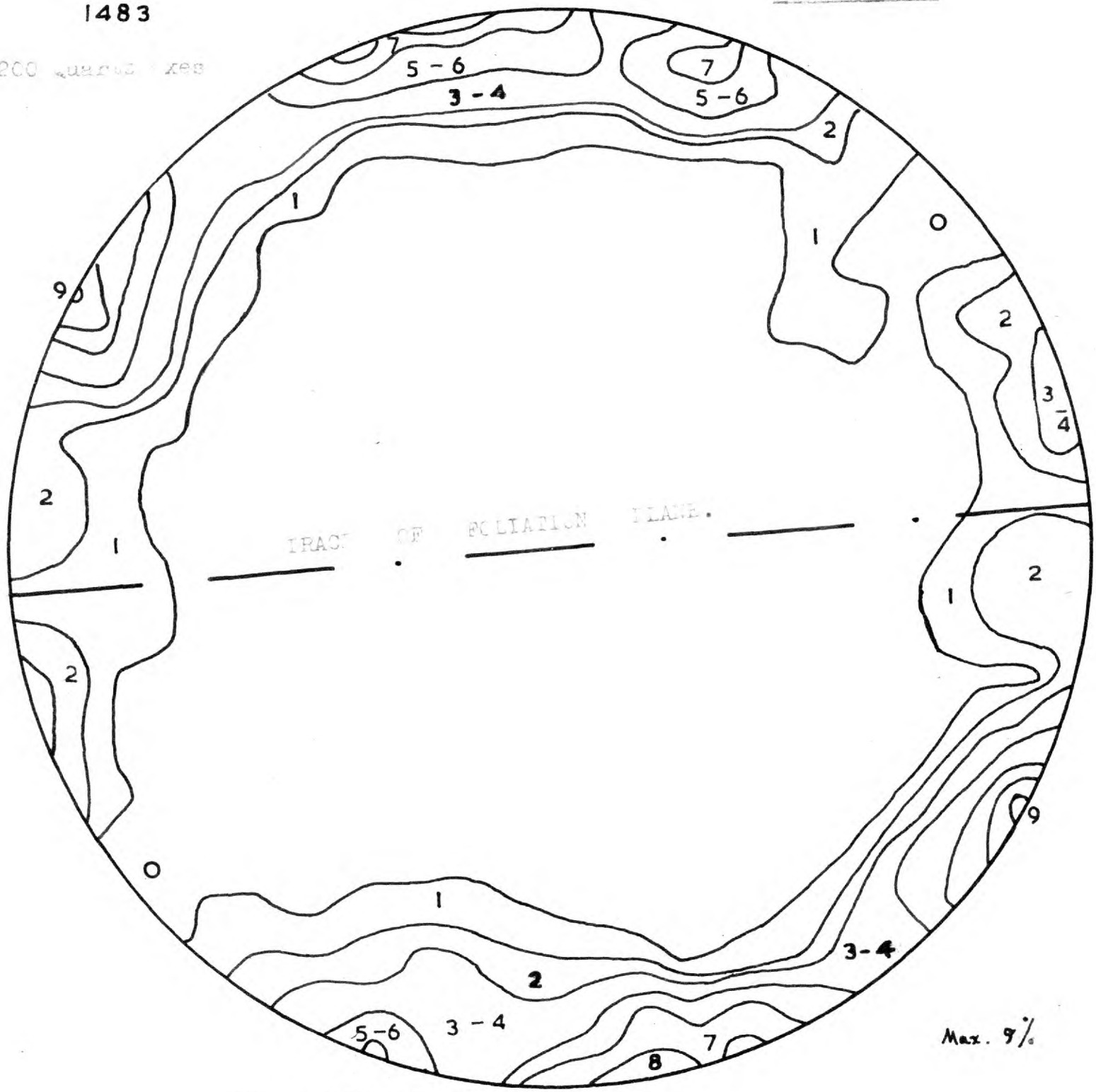
The thrusts break down the regional metamorphism of the folding (page 124). Associated with them is a set of minor structures of a very special type, developed in the a--direction, that is, parallel to the direction of movement of the thrusts. Part 2 of diagram 17, shows the orientation of these structures. The nature of the phenomenon depends on its position relative to the thrust. A traverse up to the lower thrust from well below it in the region just south of Doddsfjellet may be taken as typical. About 1000 ft. below the thrust the isoclinal overfolding (diagram 18) and its accompanying lineation are undisturbed. 400 ft. higher up a series of fractures develops, set at intervals of one inch or so. These rapidly give way to slight flexures, at similar, small distances apart, and

inconstant in their direction - buckles running into one another or splitting into smaller ruckings. They are plainly later than the north-south lineation which is 'folded' by them. Usually the buckles are more or less symmetrical, but many are overturned slightly to the south or north. About 100 ft. below the thrust-plane a lineation replaces the buckles, orientated parallel to them. This persists, obliterating the earlier north-south lineation, until the thrust itself is reached. Evidently considerable recrystallisation occurred below it. Above it, however, there occurs considerable dragging of an apparently brittle type, and a zone of mylonite about 3 in. thick is seen. The drag folding indicates the direction of overthrusting to be westward, confirming that the lineation below has developed in the a- direction. This pattern of change is seen throughout the southern range - a-lineations developing close to the thrusts, and buckles being seen throughout a considerable thickness of the rocks below. The buckling is interpreted as a result of lateral compression, presumably associated with the movement on the thrusts.

Recrystallisation is seen sporadically below as well as in the zone of a-lineation. The double headed arrows

DIAGRAM 15.

1483



Max. 9%

SECTION NORMAL TO LINEATION

of part 2 of diagram 17 record lineations, and some of these are seen to be well below the thrusts. Quartz and carbonate sweats have developed even more extensively, elongated parallel to the a-direction: blebs of calcite up to4 or 5 inches long are particularly common in the Ferrier and Isachsen groups. A quartz sweat from about 50 ft. below the lower thrust-plane on Hardiefjellet - where the north-south lineation is crossed by one running south-west/north-east - gives an interesting proof that the 'east-west' structures are later than the north-south. The 'sweat' (specimen 1483) is about 4 in. long, nearly 2 in. wide and ½ in. thick, and has developed in a mica schist. The growth of the segregation has distorted and twisted the north-south lineation in the mica schist, but the north-east/south-west lineation in the schist is not disturbed and runs unbroken across the 'sweat'. That the north-south structures were earlier was confirmed when a petrofabric diagram was made, which shewed no effect of any north-south movements: only a quartz girdle at right angles to the other lineation (diagram 19). If the north-south movements had been later, some considerable effect would certainly have been registered, perhaps even the complete obliteration of any earlier fabric.

The direction of movement of the thrusts can be measured directly from drag folds in five areas: these are shown in part 3 of diagram 17. Elsewhere the direction is inferred to be similar, from the attitude of the a-buckling.

Before proceeding to discuss the anticlinal structure of the southern range, a few remarks must be made on the mountains of the far south. On Persiskammen the dip is about 20° to the west: by the time the coast west of the mountains is reached, the value has increased to 60°. The structure is thus similar to that of the western half of the southern range, (profile E1). The nearly vertical, eastward dipping rocks of Salfjellet could be equivalent to the vertical belt which we may infer to exist some way to the west of the Persiskammen coast: or they may be the eastern limb of an anticline, the west limb being represented by the Persiskammen beds.

The evidence bearing on this question must be indirect, for the fault between the two blocks prevents a direct structural connection from being seen, and the "way up" of the beds on either side of the fault is not known. Drag-folds, if well developed, and consistent in the Salfjellet

area would indicate an anticlinal structure if they were to shew relative downward movement of the beds on the west: movement in the opposite sense would favour the other solution. In fact, drag folds were noted in only two areas, the west side moving downward in both. No satisfactory solution can be put forward with so little evidence.

Effect of Tertiary Movements on the Hecla Hoek Rocks.

The major anticlinal structure of the southern range may have been initiated at a late stage in the Caledonian movements, - later than the thrusts which it folds - but a great deal of the movement is certainly of Tertiary age. The graben faulting, which is described later in the section on Tertiary structure, has been accompanied by or has produced, a number of large and small flexures and folds in the Hecla Hoek rocks: of these the southern anticline is the largest. In Part 3 of diagram 17 , the position of the anticlinal axis has been plotted. It appears at first glance to have been displaced along 'Hecla Hoek' faults, but detailed mapping has shewn that while the position of the axis varies, the faults produce no displacement further west. In addition a subsidiary anticline and syncline in the area west of Dawespynten fail to appear on the other side of the fault which cuts them to the south.

The Hecla Hoek lines of weakness have in effect split the rocks up into blocks joined at the western end, but displaced independently of one another at the eastern end

as a result of different amounts of movement in sympathy with the great downfault of the graben. Had the fault run parallel to the Hecla Hoek trend the whole of the belt would probably have been folded as one unit. However the fault in fact runs about 30° to the trend (see diagram 17, part 1) and the resulting effect has been to produce a series of anticlines 'en echelon', developed independently of one another. An analogy may be suggested with a piece of corrugated paper which, having been torn along several lines at right angles to the corrugation, is then bent down at one side along a line not quite parallel to its corrugations. The folds do not form in one line, parallel to the 'fault movement', but parallel to the corrugations (the trend of the earlier folds), and 'en echelon'.

The independent movement of the blocks has produced considerable variation in the displacement shewn on the east-west faults. Thus at the foot of Ferrierpiggen, the anticline on the northern side of the fault is about 1000 ft. further west than the anticline on the south side: so that traversing from the west, as it were, the beds on the north side are folded down by the graben well before the beds on the south side. This local maximum of relative displacement has dragged the beds into a vertical attitude in the stretch

of ground just north of the fault. Further east, a syncline comes in on the north side and the relative displacement of the beds on the fault is then reduced to zero.

The set of dragfolds indicated in part 3 of diagram 17 has developed as a result of relative movement of this kind.

The complex fault system of Sesshogda does not continue within the Hecla Hoek rocks on the south side of Selvagen; a great tear fault, running through Scotiadalen, displaces it about two and a half miles to the east. It is this fault which produces the extreme distortion and shattering seen along the southern shore of Selvagen.

The effect upon the Hecla Hoek has been to produce a great curve in the fold trend, shewn in diagram 17 - part 1, and a consequent swing in the direction of the late buckling - part 2. There seems strong evidence that the 'rotation' in the block <u>above</u> the lower thrust has been more extensive than below: that is, that Tertiary movements, along the <u>lower</u> thrust at least, have occurred. These movements have produced the discordant relationship on either side of the lower thrust - in the north - shewn by the fold trend in part 1 of the diagram, and by the orientation of buckling in part 2. The fault which

separates the long wedge of rocks-running from the divide of Scotiadalen to the south shore of Selvagen-from the rest of the rocks of the southern division, apparently shews a displacement in an opposite sense to that of the great tear fault. Since the dip of the beds is only about 30°, however, the surface displacement could be produced by a downthrow to the north of about 2,000 ft. But the Tertiary displacement along the Scotiadalen fault cannot have a great vertical component; this fault line, however, was probably active after the Caledonian folding. It has already been pointed out that neither structure nor stratigraphy in the Hecla Hoek can be correlated on the two sides of the dislocation. The downfaulting on the north side of the smaller fault mentioned above suggests that the Scotiadalen fault itself may have a similar downthrow. Other features point to the same conclusion, particularly the presence of basic sills in the southern range, but no feeder dykes in the northern half of the island. The consistently higher grade of metamorphism in the south, perhaps suggests the same thing, but no certain conclusion can be drawn.

The other Tertiary effects on the Hecla Hoek rocks are comparatively minor - consisting only of small folds. They are shewn in various of the profiles,-folding, for example, the recumbent Charles anticline on Scotiafjellet and at the east end of Omondryggen. All Tertiary structures within the Hecla Hoek rocks are summarised in diagram 20, which may be considered in conjunction with the profiles.

CHAPTER IV. M E T A M O R P H I S M.

1. The Sediments.

The general pattern of regional metamorphism in Prince Charles Foreland is of no great significance in itself, since the orientation of the island, parallel to the folds, prevents the study revealing changes taking place across the Caledonian trend.

In conversation Weiss has described the state of metamorphism in the adjacent area of the mainland (south of St.John's bay), as generally of biotite grade, with garnets developing in places. It seems obvious that the direction of most significant change in metamorphic condition should be across the trend, and the Foreland work lacks perspective until more is known from St. John's bay and the north-western part of the mainland.

The quartzites and limestones show little or no mineralogical reconstruction during metamorphism, apart from straightforward recrystallisation. The semipelitic rocks are far less sensitive to changing conditions than the pelitic rocks, and it is largely with these that this study deals.

The upper structural unit, it will be recalled, outcrops continually over the northernmost part of the island, and as outliers on higher peaks further south. In the north

little more than diagenetic changes have occurred: these become progressively more advanced further south, but the rocks even there are hardly higher than of "chlorite grade".

Slides 121, 1388, 1398, 1327, 1337, 1351, 1356, 1358, demonstrate very clearly the sequence of changes which occur as the rocks begin to recrystallise.

121 is a rock from the Barents group, on Barentsfjellet itself: The pelitic bands are dotted with oval segregations about 0.5 mms. across, - authigenic growths of chlorite, often enclosing but not disturbing the quartz grains. 1388 is a fine-grained slate: a poor cleavage cutting across the bedding has developed as a result of the growth of sericite wisps. This is in one of the banded silty slates of the Conqueror group from the east end of St.Andreashaugane Slide 1398, from the top of the Conqueror group at the west end of that mountain has been microphotographed - plate . With its undistorted oolites it serves to illustrate very strikingly how little deformation and metamorphism have affected these rocks.

1327 and 1337 from Hellandfjellet a little further south, show the beginnings of more thorough recrystallisation. The small amount of carbonate matter in 1327 is separating into long thin patches of lath-shaped crystals parallel to the bedding (still perfectly preserved). In 1337 the quartz is locally segregating into spots about 0.5 mms. across: Mica is beginning to recrystallise - chlorite is absent -

sericite is growing parallel to the poorly developed cleavage. 1351 - a typical slate from the Conqueror group at the head of Murraybreen, shows a more advanced stage of recrystallisation, with long streaks and lenses of quartz and carbonate, in places reaching 0.4 mms. across. 1356 and 1358 from the Barents group, in the same area, show a rather more advanced condition; the original sedimentary layering is far less clearly preserved - quartz is separating into tiny elongated lenses interspersed within the sericite meshwork, less fine grained here than in the previous slides. The cleavage is seen in the field to be a feature developed parallel to the axial planes of the folds: the recrystallisation of sericite which produces the cleavage is thus dated as contemporaneous with movement.

In the structural unit below - Unit 4, the Charles anticline - the trend towards progressively greater metamorphism southwards is reversed. In the central range the metamorphism is of biotite grade; further south it is almost non-existent.

Slides 1841, 1153, 1190, 460i, 460ii, 462, 418, 1249 and 1375 - are arranged in geographical order from south to north, (that is from Ormondryggen to Boureefjellet). 1841 from the Fuglehuk group in the south is as little affected by metamorphism as the rocks in the far north: wisps of sericite are growing as cleavage develops, and quartz is beginning to

recrystallise.

In the central range however, slide 1190 from the Conqueror group east of Monacofjellet shows large biotite crystals almost 1 mm. in average dimension - plate 27c.

The rock is banded and semipelitic, original quartz rich bands still indicating bedding. The biotite is markedly pleochroic from almost colourless to an unpleasant slightly foxy brown. There seems at a glance to be no preferred orientation. The curious colour, and the setting, -with very low grade rocks to north and south- suggested the possibility that the mineral was in fact stilpnomelane, which typically occurs in a low grade setting, and may be mistaken for biotite. An X-ray powder photograph was consequently made and compared to that of biotite from a Cornish pegmatite. The diffraction patterns were substantially identical, and in sharp contrast to that obtained from stilpnomelane.

The curious colour is a feature resulting from the intense brecciation the rock has received after the biotite was formed. The crystals are fractured and buckled, the cleavage planes being violently distorted; some of the grains are pulled into fragments, and most show large patches in which the birefringence has so decreased that under crossed nicols it is entirely masked by the brown body-colour of the mineral.

The biotite on closer inspection reveals preferred

orientation in two attitudes (corresponding presumably to two generations). Some crystals lie roughly parallel to the stratification, others, generally larger, lie at almost 90° to this. Both sets are too much distorted by brecciation to allow one to say which is the earlier.

Slide 1153 from the Barents group on the east face of Parnasset is very similar. Again the curious double generation of biotite is seen, and this time despite the strong brecciation it is clear that the larger crystals, at 90° to the bedding are later, and enclose those parallel to the bedding. The significance of these facts is not plain. From the distribution of brecciated rocks it is clear that the brecciation is part of the folding history. That even the earlier generation of biotite has a preferred orientation is taken to mean that forces were already operating - Biotite thus began to grow after the movements began, and was broken down again in later stages of extreme movement.

Slide 418 (from the Scotia group at the base of the south-west ridge of Rudmosefjellet - see profile B6), and slide 1249 from below the great thrust plane under the summit, both show the effects of overthrusting. Biotite (in the former case, as smaller crystals than in the two slides just described) is again mechanically broken up - in places forming chlorite - but retaining the brown colour of biotite: slide 1249, in particular, shows violent deformation.

Slide 1375 is from the Pinkie group on Boureefjellet,

apparently well below the overthrust mass of the upper structural unit. But here again the slide shows the sequence of events :- growth of biotite - later brecciation ; this time, however, the biotite has a single preferred orientation parallel to the stratification, and brecciation was evidently followed by a considerable recrystallisation of the carbonate material which makes up quite a large part of the rock. Here, in contrast to the elongated lath shaped carbonate patches developed elsewhere in brecciated rocks of this kind there is apparently no habit orientation. Possibly this recrystallisation was a late event after movements had more or less ceased.

In the pelitic rocks of the Scotia series (presumably the central part of the group from the evidence on the Scotia succession presented in Chapter II) there are preserved on Monacofjellet brecciated rocks which contain staurolite - slides 460i, 460ii, 462. The rock (plate 27d) was evidently coarse textured, with staurolite crystals reaching 12 mms. in length and large porphyroblasts of plagioclase (probably albite) and of mica. These are all now fractured broken-down relics in a mush of sericite, quartz and carbonate. The staurolite is intensely cracked and considerably altered to sericite. One or two former staurolites can only be identified by the pattern of quartz inclusions left in the sericite pseudomorphs. Considerable disorientation of the various parts of the large crystals is strikingly shewn

when they are close to extinction under crossed nicols. The plagioclase is intensely sericitised, but twinned patches still remain, together with large quartz inclusions.

South of Scotiadalen the metamorphism is more or less uniformly of biotite grade. There are no very pure pelitic rocks here, and in most of the slides described below the pelitic component constitutes less than 50% of the rock.

Slide 821 from the Ferrier group north-east of Doddsfjellet is typical of the rocks of that part of the southern range. The assemblage is 50% quartz, 30% carbonate, and 20% mica - the whole having recrystallised completely. Of the mica about 60% is biotite, 40% muscovite; the two growing happily together, with a very strong preferred orientation parallel to the schistosity.

A selection of slides from Hannayfjellet - numbers 853, 857, 877 - from various groups and rock types, all show similar features: complete or almost complete recrystallisation, the development of muscovite, or biotite, or both from the pelitic component of the sediment. Frequently the micas are involved in small folds (of the flowing type that the structural work has shewn to be parallel to the major trend). There it is clear from the bent curving flakes that recrystallisation and growth were continuous as movement occurred. If growth were earlier, the crystals would fracture in conforming

to later folds: if they were later they would not follow the intricate crenulations.

Slides from Hardiefjellet again show complete recrystallisation, associated with the growth of small porphyroblasts of albite - up to 1.2 mms. - often oval and rimmed by a zone of small quartz crystals. 1480 and 1482 are particularly affected by the east-west buckling which is associated with the forward movement of the great southern thrust-planes. Here it is clear in a section at right angles to the puckering, that it is an event later than the growth of micas, which are fractured and distorted by a series of rucks set at about 30° to the foliation. In 1483, however, a slide of the quartz 'sweat' which is elongated parallel to the east-west lineation (see p.108) the growth of quartz is contemporaneous with the movement and shows no rucking. The energy of the overthrusting evidently produced recrystallisation in thin zones. Just above, breakdown is once more noted, chlorite being produced along thin shear zones associated with the buckling. 1488 is a particularly good example of many slides which show muscovite and biotite growing at the same time in optical continuity. In 1489 from just below the lower southern thrust-plane, muscovite exceeds biotite in quantity, the latter being strongly pleochroic from medium brown to a dark brownish green. Chlorite is forming throughout the rock, from the breakdown of biotite: it is strongly pleochroic, from almost colourless to deep green, some giving

anomalous red-brown polarisation tints under crossed nicols. Felspar porphyroblasts are common, about 0.4 mms. across: over half are of albite, but the rest show simple twinning, and react to staining tests for potassium. Slides from Methuenfjellet show no new features, merely confirming the above conclusions, that recrystallisation and growth of micas and felspar were contemporaneous with the main movement; the later thrusts broke down the mica to chlorite throughout the rock, or in localised zones of shearing.

Slide 2056 of a limestone with a considerable quantity of pelitic material and quartz, shows most unusual features: it is illustrated in plate 28a. Carbonate-quartz bands have simply recrystallised, but in clay-limestone bands there are abundant large flakes of chlorite (1 mm. across, 0.4 mms. thick), green in hand specimen, but colourless in thin section, and non-pleochroic. The large size and lack of a characteristic chlorite-green colour, prompted the making of an X-ray powder photograph: this definitely confirmed the mineral is chlorite. There are also a few crystals of pale brown biotite. The large irregular, (almost opaque) crystals shown in plate are rutile. The crystal in the central strip of the field photographed is one of several which show a refractive index greater than 1.9 and poor cleavages, mutually at right angles; the mineral is uniaxial, optically positive. This rules out all but a very few minerals, of which only zircon and sphene (which may sometimes be

uniaxial) seem at all likely. It is probably zircon, though certainly of an unusually large size. In either case the sediment must have been of a most unusual composition.

Slide 685A from Salfjellet in the far south, shows muscovite and chlorite growing contemporaneously with the small scale folding.

The regional pattern, then, is of a uniformly biotite-grade of metamorphism south of Scotiadalen. In the northern half of the island, the upper structural unit shows progressive changes going southward, within the chlorite grade. The lower unit, of the Charles anticline, is of biotite (-staurolite) grade in the north, of chlorite grade in the south. Metamorphism coincided in time with the folding: no minerals, except perhaps carbonate, recrystallised later.

The Occurrences of Chloritoid.

Quite independent of the regional pattern outlined above, is the distribution of chloritoid, which is developed throughout the island in all of these metamorphic environments. All the occurrences are characterised by the coincidence of two conditions : of structure, and of rock - composition.

Chloritoid is developed only in certain rocks of the Barents, Scotia and Kerr groups - invariable green and grey pelitic rocks, with or without a little quartz. Further, it is only developed where these beds of suitable composition are affected by particularly intense movement.

The Barents group may be taken as the first example. On Barentsfjellet beds of suitable composition occur but are not affected by violent movement - isoclinal folding has been the main form of accommodation. In the region east of Hellandfjellet and Leefjellet, however, the group comes into the zone of overthrusting, where units 1 and 2 are seen to override structural unit 3. (see diagram 14). There below the thrust chloritoid develops strongly - not everywhere, but only in green pelitic rocks. Within a few feet of rocks like specimen 1388 which was described (page 117) as showing only the first signs of recrystallisation, and not far from the location of the undistorted oolitic limestone shown in plate 28b , there is developed a rock in

which stubbly laths of chloritoid reach over 1 mm. in length, and 0.4 mms. in width, chloritoid making 40% of the rock: the rest consists of patches of quartz in a framework of muscovite. The chloritoid has a fairly strong preferred orientation parallel to the schistosity. From a little further south, associated with the same thrust, come the rocks of slides 1311 and 1312. The former shows needles of chloritoid about 0.6 mms. long in a poorly segregated mesh of fine quartz and muscovite. Again there is a preferred orientation in the chloritoid, parallel to the schistosity, but only about half of the crystals conform to this. The rest are haphazardly arranged. There is no sign that these latter are of different generation: they are obviously contemporaneous. In slide 1312, distortion has evidently been more intense, for a former quartzite band, recrystallised, has later been torn into a series of lenses. Individual quartzes have in places been drawn out into greatly attenuated streaks, and all show a great amount of strain under crossed nicols; occasionally an anomalous blue indicates extreme strain in the atomic lattice-work. The gaps are filled by numerous very large magnetites - segregations from the surrounding rock. The chloritoid is more stubby and a little larger than in 1311. Far from being distorted by the movement as is the quartz, it is obviously growing in association with that movement, individual laths following

the folds which distort the drawn out quartz grains.

Rocks from the Barents group, at the head of Murray-breen have already been described (page 118). Reference to profile B4 will show the position of the attenuated Barents group (on the ridge well east of Boureefjellet). Intense movement between the overthrust Conqueror group and the Fuglehuk group below has attenuated the Barents group so much that its thickness is now only 300ft. Slides 407, 406B and 1362 illustrate the progressive development of chloritoid in this zone of extreme movement. 407, containing rather a high percentage of quartz, shows intricate small scale isoclinal over-folding of mica and quartz bands, the whole slide being cut by a network of subparallel shear-planes along which the rock is ground down to a fine, nearly opaque dust. Long needles of chloritoid can be seen developing in places, curving round the violent folds. In 1362 and 406B chloritoid laths reach an average of 1 mm. in length. Plate 18c , of 406B shows very beautifully the way in which the chloritoid laths follow the folds: instead of being cracked, they bend around the crenulations, with continuous growth preventing disruption. Set opposite is the photograph of the oolitic limestone from close by, to indicate the low grade setting.

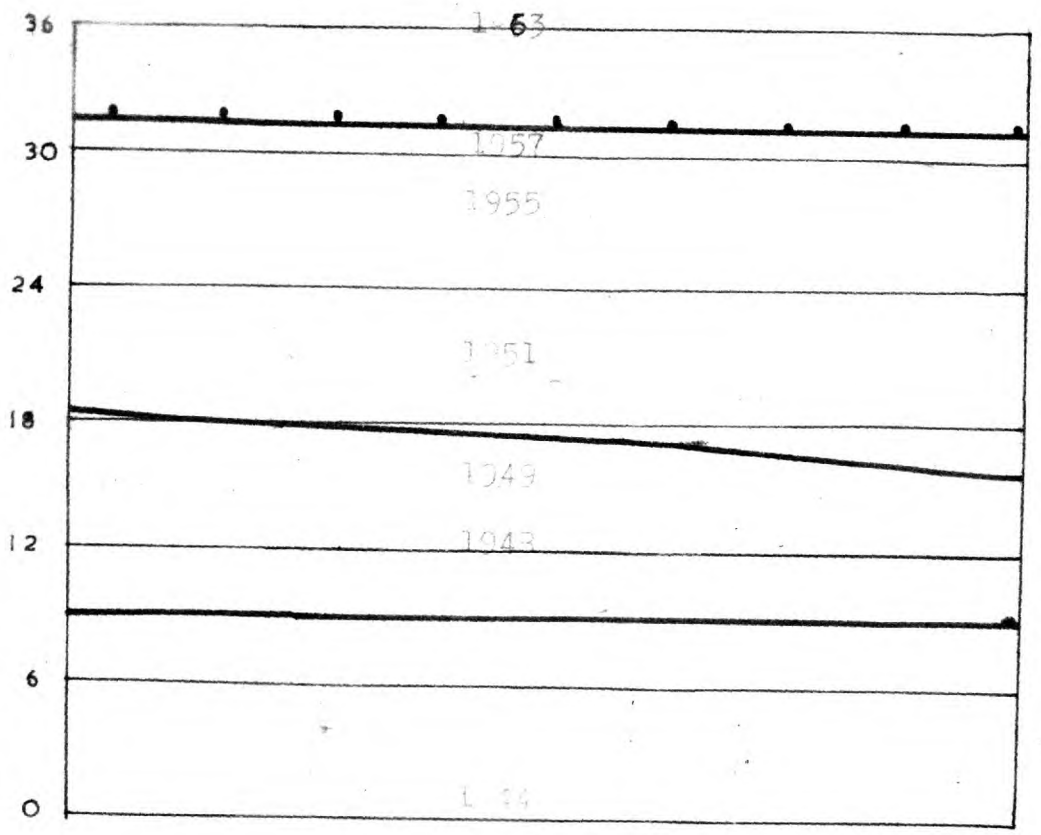
In the central structural unit of the Charles anticline, rocks of the green pelitic facies seen in the north seem to be

sheared out or lost by facies changes, except perhaps in one or two localities. Below the overthrust upper structural unit on south Rudmosefjellet occurs a zone of intense movement, the autoclastically mixed rocks of which have been mapped. From within this zone on "the Citadel", below the lens of epidiorites and mylonites, comes specimen 1259 with ½ mm. laths of chloritoid.

In the Scotia group around Scotia-fjellet itself are a series of occurrences of chloritoid which were noted before the various subdivisions of the Scotia group were mapped in detail. The occurrences were all later found to lie in one particular part of the series only : and to be located where movement was obviously intense. Slide 1001, which shows clots and radiating needles of chloritoid in a fine mesh of quartz and muscovite, is from the south of the small area shewn on diagram 9 :p.64 the location is indicated by a black circle. Here the central grey slate horizons of the group are brought into the zone of intense deformation where the inverted Scotia group rocks ride forward over the Fuglehuk quartzites, the right way up. Profile C10 indicates the structural situation, on this line of extreme movement.

The other occurrences in this area are on the northwest ridge of Scotiafjellet at a height of about 1500ft. Here a series of slides has developed within the Scotia group,

Diagram 31.



associated with the advance of the recumbent antidline. The country rocks are no more than slates and this locality was selected as an excellent example of the formation of chloritoid in a practically unmetamorphosed environment. Slides 1944, 1948, 1949, 1951 and 1955 to 1966 were studied in detail, and reveal a consistent pattern of changes occurring as each thrust is approached.

The figure (diagram 21) opposite is a diagrammatic section showing the true relation of the various outcrops. (The beds actually have quite a high dip).

Below the lowest thrust are thin sections 1944, 1948 and 1949. 1944 has been microphotographed, plate 29a, to illustrate the very first stage of the process, in slates 18ft. below the first thrust. Tiny laths of chloritoid can be seen developing haphazardly in the mass of the rock, and - more plainly visible - in the small quartz segregations. In slide 1948 the quartz - chloritoid patches are more numerous and larger, forming streaks and lenses; mica laminae are less continuous as a result of this developing segregation. A good deal more chloritoid is seen now, usually in the quartz areas; they are larger laths, but still stubby in shape. The whole rock begins to take on a much more fully recrystallised appearance than 1944.

In specimen 1949 less than 3ft. below the thrust plane, the chloritoid develops on a large scale - 1 mm. patches and lenses of quartz and chloritoid lie amid thick,

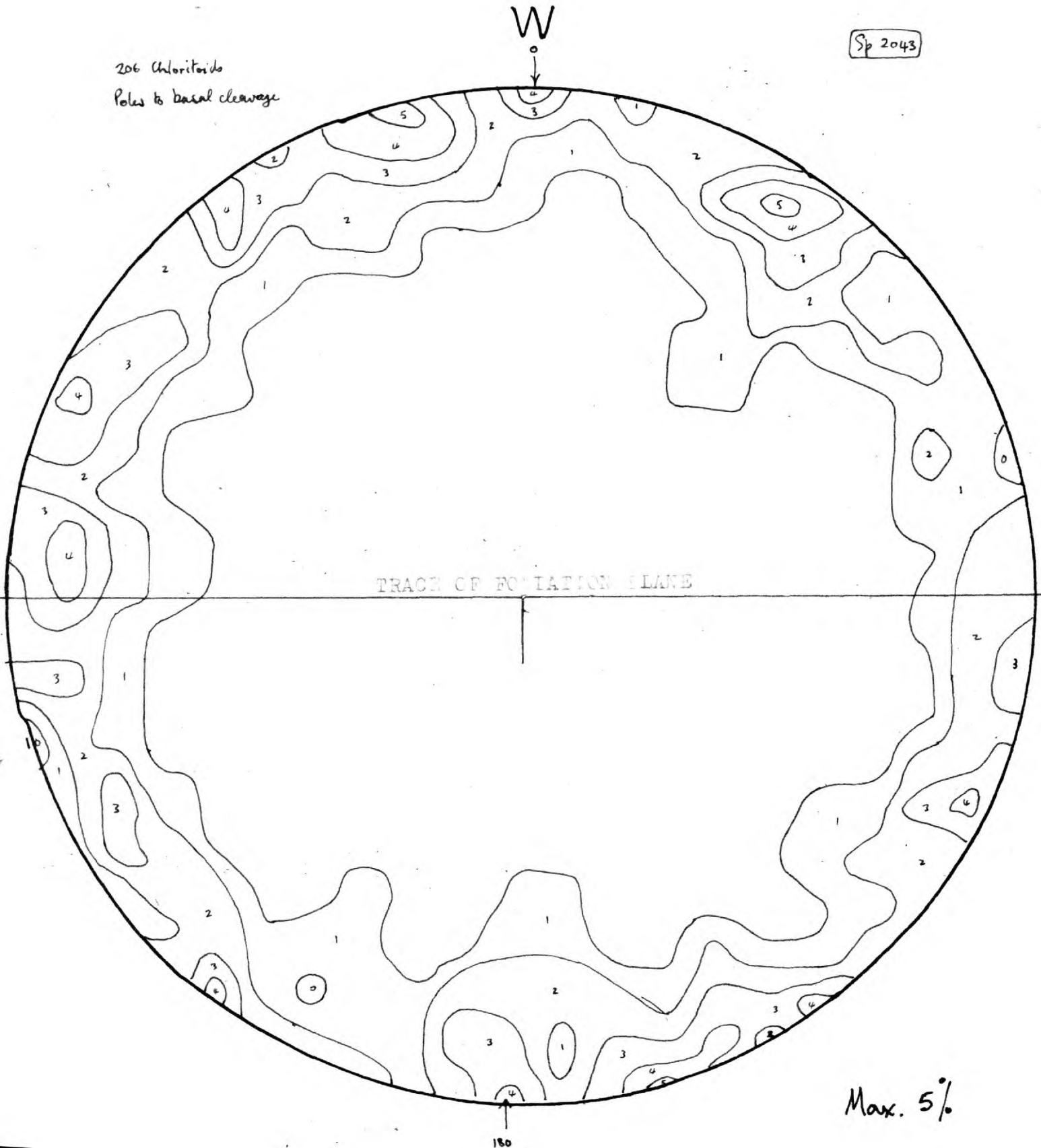
intersecting bands of mica: and there is a marked differentiation into these separate areas (see plate 29b). Chloritoid now forms rosettes and long needles in the quartz segregations: within the mica, however, the form is always lath shaped, mostly sub-parallel to the developing schistosity: the mica is fine-grained.

From 3ft. above the lowest thrust comes 1951, very similar to slide 1948, except that ~~the~~ late shearing has produced large amounts of retrograde chlorite (from mica) but this has not broken down the chloritoid. In 1955, 12ft. above the lower thrust, we have returned to the condition of 1944 - a slate dotted with tiny chloritoid laths.

Abruptly a zone of distortion follows, a quartzose band showing fantastic strain effects - with the production of Bohm lamellae in a patchwork of greatly elongated crystals (plate 29c). Abundant chloritoid, in rosettes and needles, develops in the pelitic bands (only partly recrystallised) bordering the quartz. Chloritoid can be seen in the zone on the left of the photograph. Slide 1957 shews even more extreme distortion in the quartz bands : patches of recrystallised mica, have subsequently been puckered to such an extent as to simulate under crossed nicols, the appearance of a crumpled piece of shot silk. Within this are abundant laths and rosettes of chloritoid.

The rest of the slides conform to the sequences described above and there is no need to describe them in detail.

Diagram 21A.


W
0
Sp 2043
206 Chloritoids
Poles to basal cleavage
TRACE OF FOLIATION PLANE
180
Max. 5%

The photograph, (plate 296), is of 1963, typical of the stage described under slide 1949. 1965 and 1966 are slates from the top of the chloritoid zone, about 40ft. above the base, and are, as it were, mirror images of the first slide, 1944. Beyond this the slates are unaffected.

In the southern half of the island, chloritoid is developed in green and grey pelitic rocks of the Kerr group, in a biotite-grade environment. The resulting rocks are exactly similar to those described already, though occasionally they are of coarser texture. Along the line of the upper of the two great southern thrust-planes - on Alasdairhornet and in Scotiadalen - a belt of chloritoid rocks has developed - slides 931B, 941.

The thick chloritoid belt in the vertically disposed rocks of the east coast of Peachflya, shows considerable quartz veining and buckling associated with the westward thrusting, but the sea to the west prevents one from being able to say that these rocks are definitely developed below an overthrust block. A petrofabric diagram was made from 200 measurements of the attitudes of basal cleavage in the chloritoid flakes of slide 2043. This is reproduced opposite, the slide being taken at right angles to the almost vertical lineation. The diagram is thus practically 'horizontal': the foliation is plotted. The girdle shews the same relationship to the vertical westward

lineation, as did the quartz girdle of specimen 1483 (the quartz 'sweat' elongate parallel to the movement of the thrust - p. 108). From this it seems probable that here too the fabric in the chloritoid indicates its association with westward thrusting.

In all those rocks described above which have been affected by later stage disruptions, the chloritoid has remained undisturbed, while other minerals were broken down. The single exception to this is seen in slide 1505, from the south side of Selvagen close up against the great Tertiary tear fault of Scotiadalen. Here under extreme retrogressive conditions some of the chloritoid has broken down to a fine mesh of chlorite.

Summary.

Chloritoid develops in complete discordance with the pattern of regional metamorphism. It occurs in any zone, wherever there is a coincidence of certain critical conditions of rock composition and structural setting. Thus, only pelitic rocks of suitable composition are capable of producing chloritoid, and then only in zones of extreme movement. The mineral is extremely stable.

PLATE 27. a) to d).



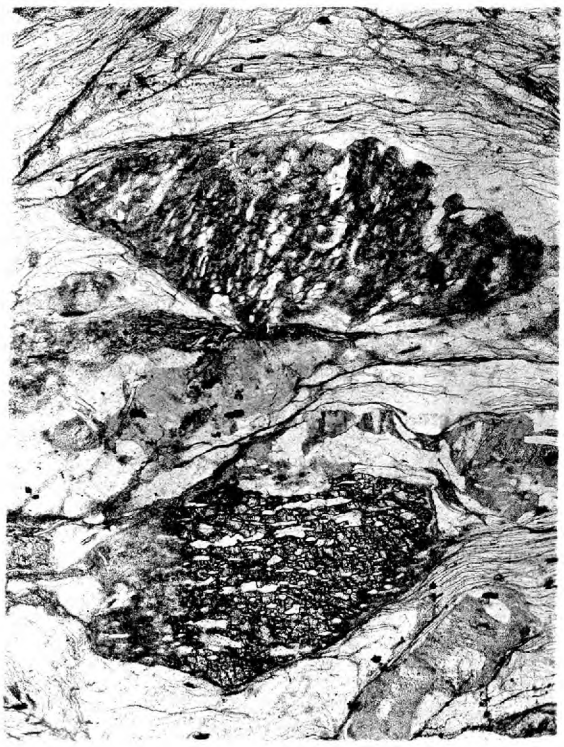
a). 1866 O.L. 25.



b). 1867 O.L. 25.

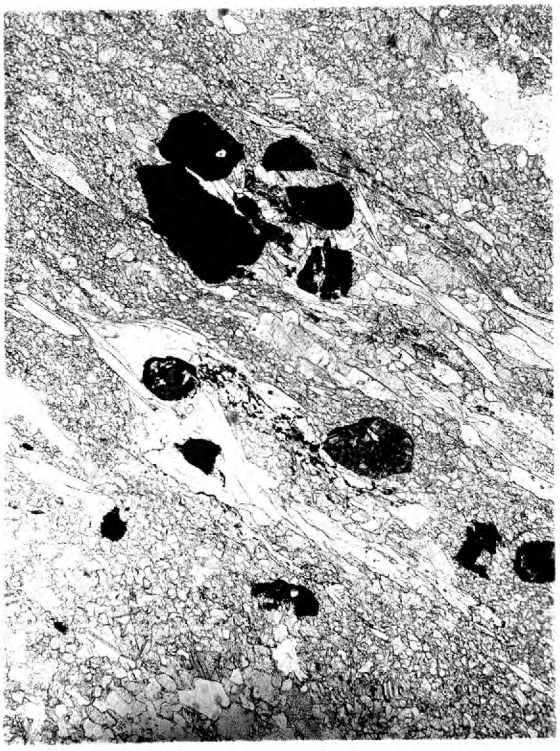


c) 1190 O.L. 25.

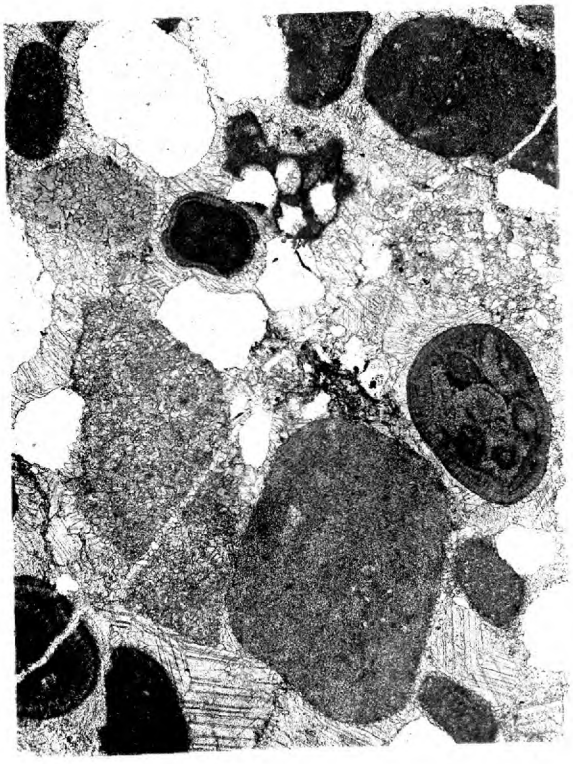


d) 460A O.L. 25.

PLATE 28. a) to c).



a). 2056. O.L. 25.



b). 1398. O.L. 25



c). 406B. O.L. 25.



a). 1944. O.L. 25.



b). 1963. O.L. 25



c). 1957. M. 35

2. The Epidiorites

The distribution of epidiorites is shown on the geological maps A-E. They are confined to the southern range, with the exception of a single area in the centre of the island.

Almost everywhere the sills, acting as struts in a pile of incompetent sediments, have taken the bulk of the stress and are intensely sheared. The occurrence of sheared hypabyssal rocks in unsheared country rock is a well known phenomenon. Over great stretches, then, the sills are represented by bands of chlorite schist, often thinning and lensing out. Occasionally within these sheared rocks are small pods and lenses which have escaped complete breakdown, and it is these that demonstrate that the chlorite schists are retrograde dolerites, and not metamorphosed tuffs or sediments. The most southerly of the sills is 6ft. thick, occurring at a height of 800ft. on the east ridge of Methuenfjellet. The central 4ft. is less deformed than the edge; from the centre is specimen 791 - (microphotograph, plate 30a). The rock consists of about 40% to 50% amphibole, 30% chlorite, 10% quartz, 5% sphene, 5% calcite, 1% biotite, <1% magnetite and plagioclase. The amphiboles are hornblendes, pleochroic from colourless to pale green, and make up an extraordinarily large part of the rock. No relics of original pyroxene appear. The

microphotograph shows well the retrograde texture of the rock. Three or four large amphiboles are seen, mostly in the upper half of the photograph. The small opaque crystal just below and left of the centre is magnetite. The dark meshwork throughout the rock is of chlorite; some granular patches and clots of sphene can just be distinguished at the top right. Quartz and carbonate make up the white areas - the two being impossible to distinguish in the photograph. The few plagioclases present are between andesine and oligoclase in composition (An.30).

About 1ft. above 791, is a light green rock which gave slide 792. Here there is no amphibole, but a great quantity of plagioclase, and smaller amounts of chlorite, quartz and carbonate. The plagioclase is andesine, (An_{35}) occurring as numerous small crystals throughout the rock.

On either side of the central four feet which has been described above lie one-foot zones of chlorite schist, clearly formed at the edges of the sill by more thorough shearing. The microphotograph, plate 30b, is of slide 790, from the base; the assemblage is calcite, chlorite, muscovite and quartz, with minor amounts of magnetite. The composition is roughly: calcite 35%, quartz 30%, chlorite 20%, biotite 15%. The relations of the minerals are clearly shewn in the photograph, the twinning of calcite - which appears in patches - distinguishing it from the smaller

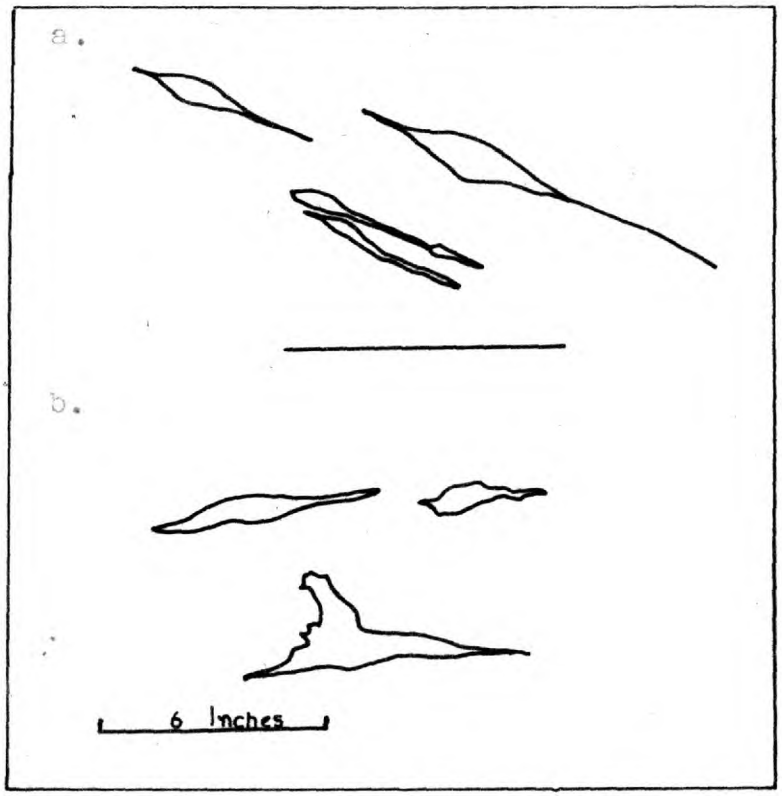
quartzes scattered throughout the rock; biotite shows up amid the chlorite by its greater absorption. The two micas appear to be in equilibrium with one another; there is no evidence here that chlorite represents a more advanced stage of breakdown.

This rock has no suggestion of an igneous texture; it is typical of the green schists of the central parts of the southern range. Relics of original textures are not seen north of this Methuenfjellet sill until the area of Doddsfjellet is reached. Before describing the features seen there, however, it is of importance to note the differentiation which the Methuenfjellet sill shews - with a zone rich in mafic constituents, lying below a zone rich in plagioclase. It is hardly reasonable to expect a 6ft. sill to show magmatic differentiation such as is seen in stratified gabbros: cooling and crystallisation are too rapid. The phenomenon is clearly associated with metamorphism and it has preceded the shearing. This is consistent with the structural history suggested in Chapter III - the shearing being associated with the late, westward thrusting.

Two thick sills intruded into the Isachen group are seen in the area south of Selvagen, and west of Doddsfjellet. The lower one has a thickness of about 130ft. at its maximum, the higher 310ft. Both lens out to the south.

Diagram 22.

Pods in Chlorite-schists.



In the thinner sill, no igneous textures are ever preserved; the rock is a chlorite-schist similar to specimen 790. The higher sill however - though for the most part thoroughly sheared - shews pods and streaks, in places, which weather out conspicuously from the soft chlorite-schist. Diagram 22 opposite is from field sketches of the form of the pods. On the ridge north-west of Doddsfjellet, the sill is about 300ft. thick. The top 40ft. are of a dark green rock/which comes slide 1072 (microphotograph, plate 30c), about 60% of which consists of plagioclase. The composition is andesine-oligoclase, An.30 - forming large crystals 1 to 2 mm. long which have been disrupted and displaced, as is clearly seen in the photograph: the gaps are filled with fibrous chlorite aggregates. The felspars shew a great deal of sericitisation, and some replacement by epidote. The whole rock is speckled with epidote, and biotite - the latter mostly later altered to chlorite. Long laths of zoisite have developed, later to be torn into fragments: one of these is clearly visible (near extinction) just below the right hand edge of the lower of the two large felspars. The iron ore is evidently ilmenite (perhaps with a titaniferous-magnetite core), now greatly decayed to leucoxene; only a tiny opaque centre remains in most of the crystals. Many are completely altered, including two shewn in the bottom left hand corner of the picture, and at the lower right corner of the large plagioclase.

Below the dark green rock of the specimen just described, is a mass of chlorite-schist in which are numerous pods. From one of these came slide 1074 (microphotograph, plate 30). Granular areas of small epidote crystals makes 60% to 70% of the rock. Occasional plagioclases remain :- one lies a little above the centre of the photograph - considerably replaced by biotite. Many, however, are completely converted to epidote, and shew as 'ghosts' under low illumination: within these, the epidote crystals are always larger in size than elsewhere - 0.1 mm. instead of 0.02 mm. The average size of the felspars was evidently 1 to 1.5 mm.

In addition to the minerals mentioned above there is zoisite - in more equidimensional crystals than in slide 1072; and quartz is scattered throughout the rock, and occurs also in late veins about 1 mm. across, the "walls" of which are lined with large epidotes, the centre being filled with large unstrained quartzes. Three or four of these veins can be seen in the photograph e.g. one just right of the plagioclase, ranging up and down the picture. Titaniferous magnetite is seen clearly - the large grain some way below the centre, has a rim altered to leucoxene: others higher up shew no alteration.

In this same sill 2 miles further south, a detailed traverse was made, but only slight variations in composition in the chlorite schist were detected; much of the rock is

exactly similar to the example photographed from Methuen-fjellet (slide 790). Slide 2101 from 20ft. above the base of the sill, shows the rock to be ground down to a fine-grained patchwork of quartz, muscovite and magnetite, (the latter making over 10% of the rock) with medium-sized laths of green chlorite. Fairly large zoisite crystals evidently antedated the shearing, and are rolled and rounded. The later rucking, associated with the upper of the two great southern thrusts, has produced a second generation of chlorite along the axial planes of small folds.

Pods and streaks from this part of the sill have already been mentioned and sketched (diagram 22). In thin section they are extremely similar to slide 1074, described above (and microphotographed, plate 30a), the assemblage being epidote, green biotite, titaniferous-magnetite, zoisite, calcite, quartz and sphene. The magnetite here however forms large intersecting needles and laths within patches of chlorite; numerous clots of biotite are partly altered to chlorite one hundred and fifty feet above the main sill, and just below the higher southern thrust plane, is a large lens of basic rock, forming an isolated pod lying amid marbles. This is shaped like a pip, 20ft. long, 10ft. thick, elongated parallel to the general schistosity. Many shear planes cut the rock but patches of it are less broken down. Microphotograph 2134 (plate 31a) is from the central 'massive' part of the pip; it shows a large amphibole running across

the top right corner - strongly pleochroic green hornblende, the absorption scheme being: X - pale yellow-green: Y - strong olive-green: Z - strong bluish-green. The hornblendes are all lath-shaped and average 2 or 3 mm. in length; they are greatly broken up, and altered to biotite and then chlorite. There are numerous clots of biotite, throughout the rock, often showing residual shreds of hornblende. Laths of zoisite up to 1.5 mm. in length have also been fragmented and displaced - one is seen in two parts in the middle of the lower edge of the photograph. A great amount of sphene can be seen along the left side of the picture. Calcite occurs as patches (top left corner) and as rhombs within the mass of the rock, which is composed of epidote. There is no quartz.

Contact metamorphic effects.

The large pod of igneous rock described above is surrounded by a zone of serpentine a few inches thick, and by an aureole of marble about 8 to 10ft. thick, which disappears where the pod lenses out. The whole is intensely sheared.

Two feet from the serpentine edge of the pod - (which was evidently produced by the movement), yielded specimen 2138, in the thin section of which large euhedral tremolites, over 2 mm. long are seen to be abundant. They are generally aligned parallel to the schistosity and intricately disrupted,

in parts broken down to carbonate and quartz. The rest of the rock is a finely granulated mixture of quartz (40%) and carbonate (60%) with larger shreds of muscovite, a little biotite, and a few small granules of sphene.

Four feet from the pod, a pelitic limestone band has produced an assemblage rather like that of specimen 2056, (which was shown in plate 28a and was described in the remarks on regional metamorphism). Here in specimen 2139, however, there is only colourless chlorite, and a great deal of carbonate. (The rock 2056 may, then represent a regionally metamorphosed contact rock, but no intrusion was seen in that neighbourhood.) Eight feet from the intrusion, specimen 2141 is simply a spotted rock, the spots being of carbonate in a fine grained matrix of quartz and carbonate. Rather better examples of this porphyroblastic phenomenon, were noted in specimens from above the main, large sill ~~below~~ - (slides 2116, 2118, 2122, 2126). One of these - 2122 - is illustrated, plate 31b. Here the carbonate is clearly dolomite, and the fine matrix is composed of biotite, muscovite and quartz, with a good deal of magnetite. The porphyroblasts, reaching 2 mm. in diameter, have clearly pushed aside the matrix. In other specimens replacement with little distortion of the layering of the rock is seen; trails of undigested magnetite running straight through the porphyroblasts shew that growth was not accompanied by rotation. In the specimen 2122 there

may have been some shearing, as the porphyroblasts tend to be lens-shaped, the thinning ends of the lenses shewing zones of small (0.1 mm) quartz crystals. Since the contact effects must have preceded the regional metamorphism and thrusting, it is surprising that these textures should have survived at all.

The only epidiorite north of Scotidalen has already been mentioned in Chapter III. It appears below the great overthrust of the upper structural unit on the "Citadel", as a lens about 600ft. thick, and extending at least 2000ft. in one direction. Most of the rock is extremely sheared, and mylonised; only in the upper 200ft. on the 'the Citadel' are igneous relics seen, and this may be the only part of the lens which was originally an intrusive rock. Slide 1264 from the blocky cliffs which surround the peak, shows a granulated assemblage of calcite (30%), quartz (20%), magnetite (10%), zoisite (5%) and about 40% of mica, originally biotite, three-quarters of it now converted to chlorite; also a large crystal of rutile and many tiny granules (0.05 mm) of sphene. The slide shows numerous shear planes interweaving among large residual clots of zoisite, magnetite and biotite-chlorite. The two stages of breakdown, first to biotite, then to chlorite, may

correspond to the sequence noted in the pelitic rocks of this area:- regional metamorphism followed by retrograde movements. This would suggest the sill was emplaced before regional metamorphism (and folding) began. The position of the epidiorite, however, suggests that intrusion may have taken pdvantage of the thrust plane as a point of weakness, the rock being sheared by further movements. The evidence is insufficient to fix the date of intrusion in this case.

Summary.

Sheared basil sills are seen in the southern range and in one locality in the centre of the island. They are dated definitely as pre-folding: Contact metamorphosed rocks survive in one small area only. Assemblages produced from the igneous rock by the regional metamorphism are almost completely destroyed during the thrusting episode: the rocks are now nearly everywhere reduced to chlorite-schists.

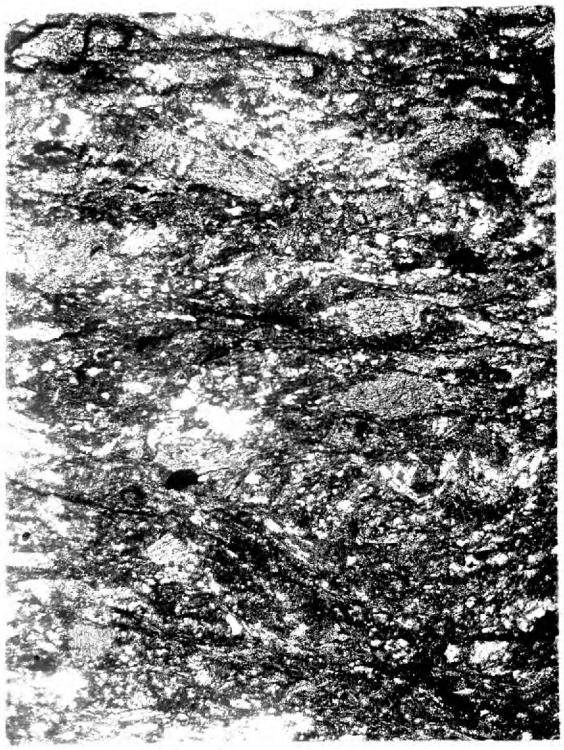
Problemmatical pyroxenite.

This is a convenient point to record the occurrence of a problemmatical pyroxenite in a small area amid the raised beaches west of Monacofjellet. The distribution

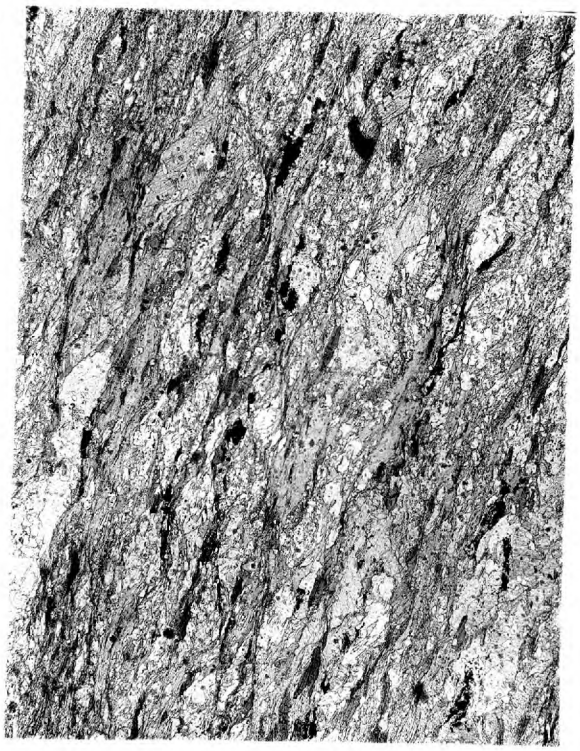
is indicated on Map B, and the setting in profiles B9 to 11. The rock is greatly granulated, but was once extremely coarse - crystals reaching over 1cm. In many specimens the rock is monominerallic - consisting solely of a colourless pyroxene, optically positive, with a large optic axial angle - either diopside or augite. In other specimens there occur subordinate amounts of a second pyroxene which is taken to be hypersthene. The rock is thus, perhaps, an extremely coarse gabbro, not fitting at all the rest of the Foreland's geology.

It is surrounded by mylonites and presumably represents a tectonic pip, squeezed out of its true setting in a higher grade environment. (Slides of this rock and the associated mylonite are numbers :- 442, 443, 444, 2069 and 2072).

PLATE 30 a) to d).



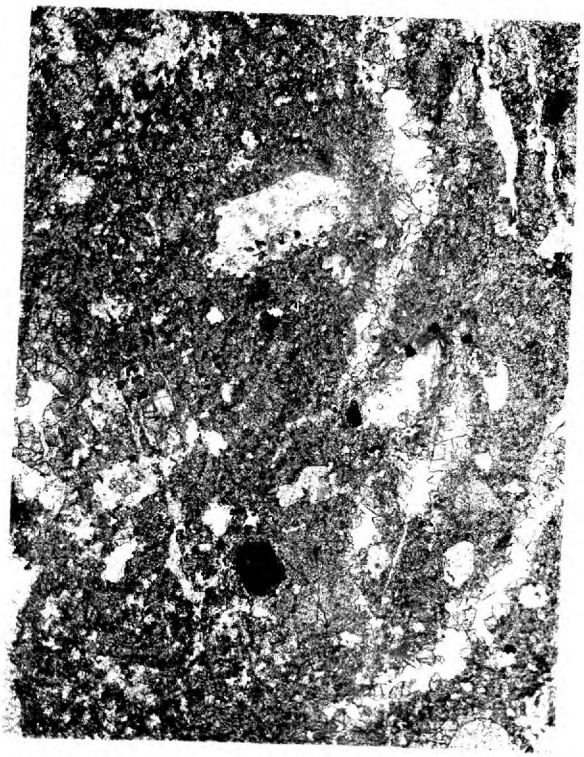
a). 791B. N. 25.



b). 790. O.L. 25.

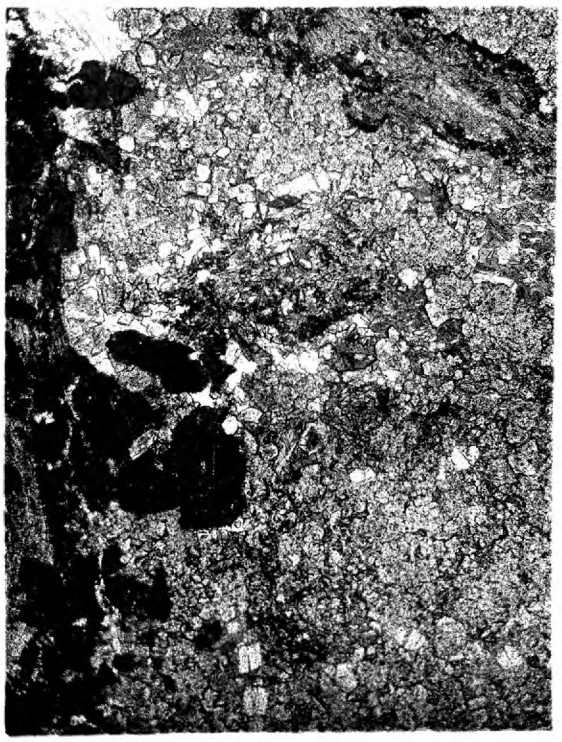


a). 1072. N. 25.



d). 1074. O.L. 25.

PLATE 31 a) and b).

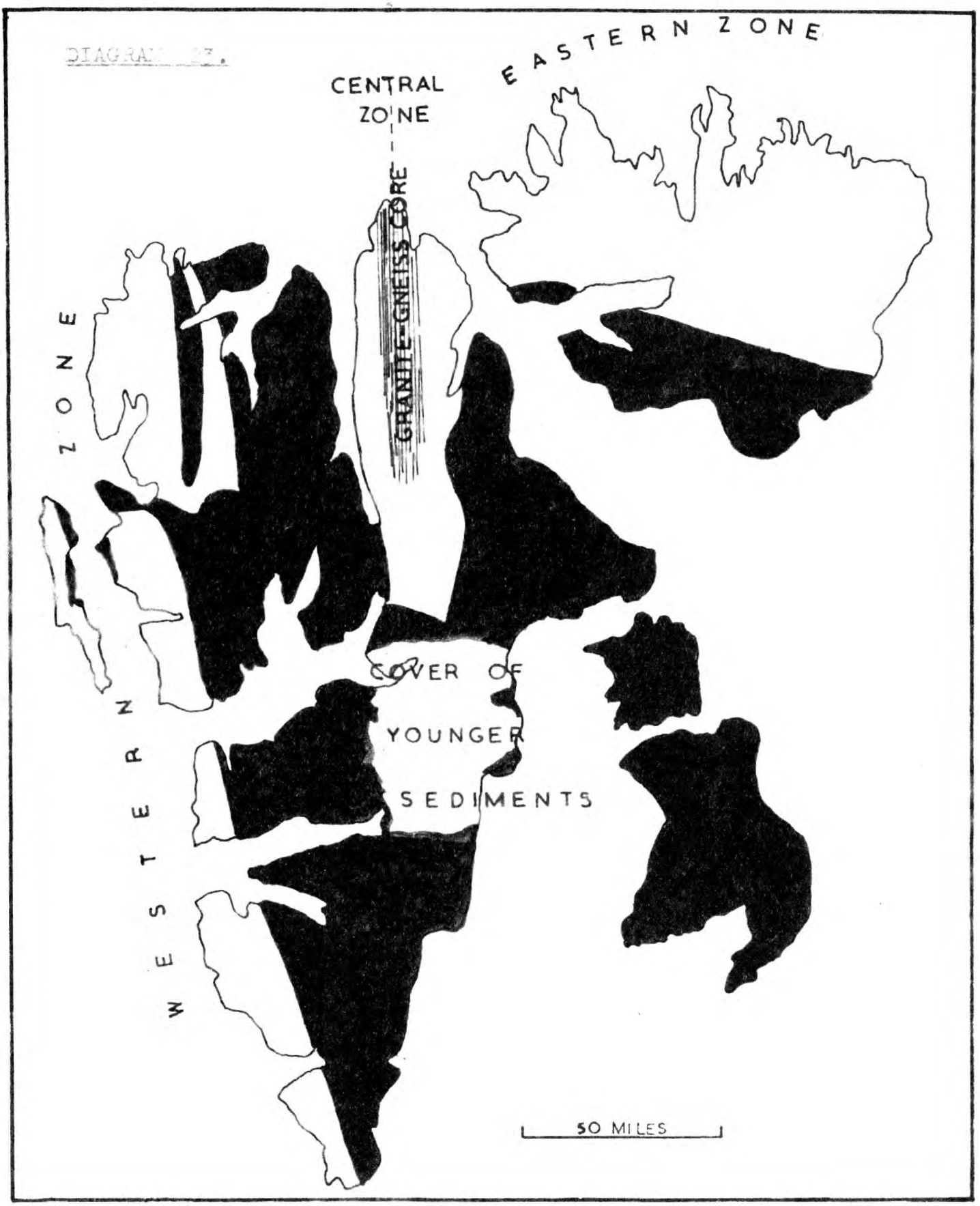


a). 2134. O.L. 25



b) 2122. O.L. 25.

DIAGRAM 27.

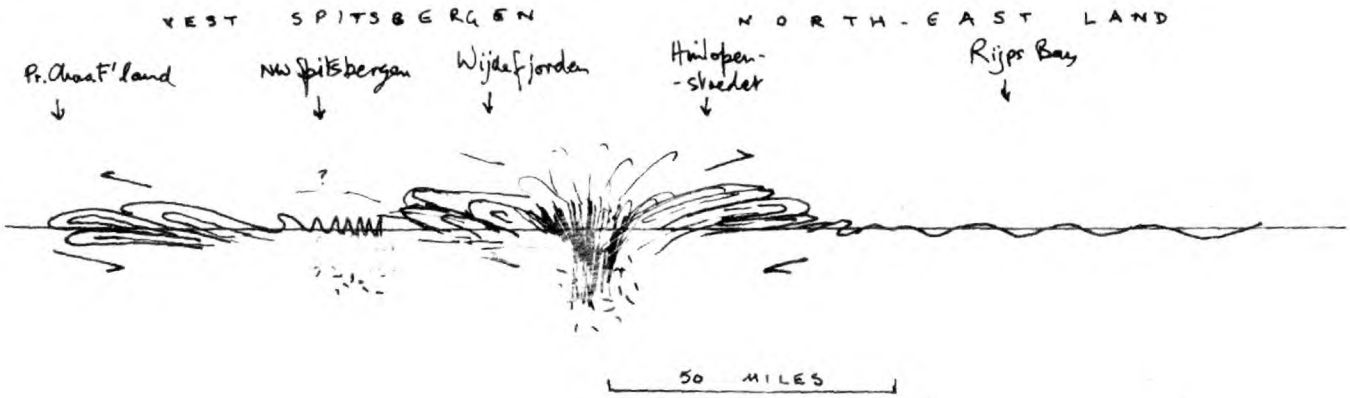

EASTERN ZONE
CENTRAL ZONE
GRANITE-GNEISS CORE
WESTERN ZONE
COVER OF YOUNGER SEDIMENTS
50 MILES

CHAPTER V. THE CALEDONIDES OF SPITSBERGEN

Before discussing the way in which this work in Prince Charles Foreland fits in with studies of the Hecla Hoek formation elsewhere in Spitsbergen, it will be as well to sketch in the major features of the pre-Devonian geology. As the map (diagram 23) indicates, Hecla Hoek rocks outcrop in three areas - a western zone (which includes Prince Charles Foreland) stretching along the coast from Sorkapp to the northwest corner of the mainland; a central zone in the northern part of the mainland - Ny Friesland; and an eastern zone represented by North-East Land. The work on Prince Charles Foreland suggests that this general division into three zones is valid geologically as well as geographically. In the central zone, the metamorphism of the sediments is high grade, with accompanying migmatisation; compression has been strong, and the rocks are tightly packed into isoclinal folds. To the east the folding gradually decreases in intensity, recumbent folds overturned to the east, giving way to open anticlines and synclines. The intensity of metamorphism falls off, and low-grade sediments are seen resting unconformably upon a basement of 'dead' Precambrian rocks. To the west of the central zone, the intense granitisation of the core in Ny Friesland also dies away, and in the coastal belt the sediments are medium or low grade. The north-west corner of the

DIAGRAM 24.

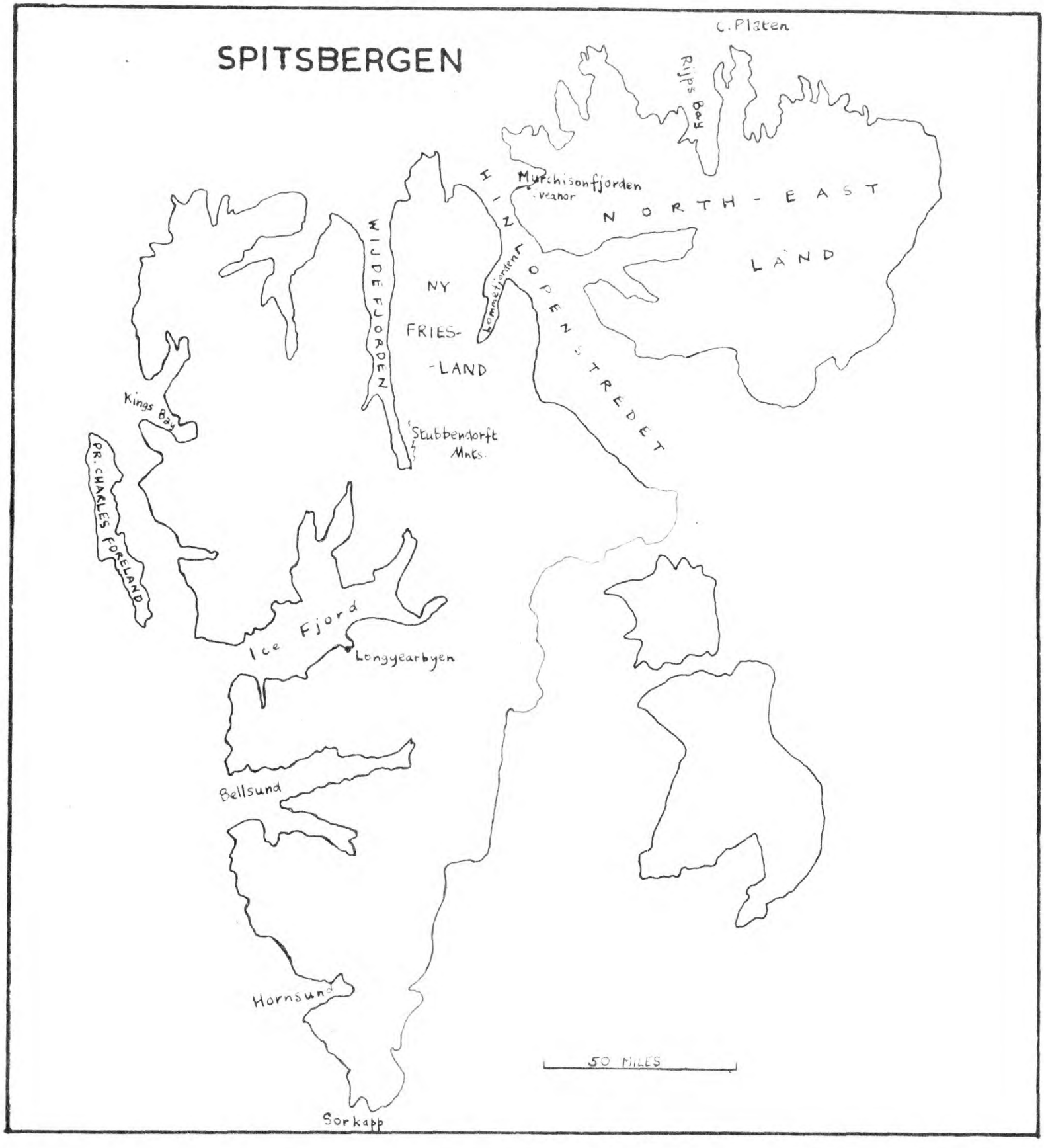
W. E.



mainland seems to provide the link connecting the coastal with the central zone; metamorphism and migmatisation is more intense there than elsewhere in the western zone.

Vitally significant is the direction of overfolding on Prince Charles Foreland. The only other area in which this crucial direction is known is the Stubendorff mountains, where Harland (1941) has shewn it to be west-ward. If we may extrapolate from these two areas, we arrive at an exciting picture of the Spitsbergen Caledonides, which is indicated diagrammatically opposite (diagram 24). The fold belt seems to take the form of a classical Kober orogen - or a tectogene. In the next chapter the implications of this idea - that both sides of a symmetrical fold belt are represented in Spitsbergen - are discussed in relation to the rest of the Caledonides of the North Atlantic-Arctic province.

The work from which this picture is drawn is mainly that of Sandford in North-East Land; Kulling around Hinlopenstredet; Blomstrand, Harland, Odell and others in Ny Friesland; Holtedahl and Schenk in the North-west part of the mainland; and Orvin in the west coast zone. Admirable commentaries on the general pre-Downtonian geology have been made by Orvin (1940) and Sandford (1950) - the latter at last establishing that there are two great series involved in the Hecla Hoek of Spitsbergen - an older, highly metamorphic division, and a younger series of sediments, which are high grade in some places, but elsewhere are little altered, and lie uncon-


SPITSBERGEN
C. Platen
Ryps Bay
Murchisonfjorden
Vegahor
NORTH-EAST
LAND
I
Z
NY
FRIES-
-LAND
WIJDE FJORDEN
Lomonosovfonna
FOJEN STREDET
Kings Bay
PR. CHARLES FORELAND
Stubbendorff Mnts.
Ice Fjord
Longyearbyen
Bellsund
Hornsund
Sorkapp
50 MILES

formably upon the older series.

The most detailed stratigraphical work on the Hecla Hoek formation is that of Oskar Kulling, who worked with the Swedish-Norwegian Arctic Expedition in the summer of 1931 (Kulling, 1934). His results will be discussed in some detail in order to provide a basis for the examination of what is known from other parts of the east and central zones, and eventually for the consideration of the possibility of correlating the rocks with those of the western zone, particularly on Prince Charles Foreland.

From the areas immediately adjacent to the (E. and W.) coasts of Hinlopenstredet, Kulling formulated a sedimentary succession, which can be summarised thus :-

4. Cape Sparre Formation. 2,600 to 2,800ft.
   Dolomites, slates, quartzites. Fossiliferous horizon at top.
3. Svеanor Formation. c.500ft.
   Tillite with varved marls. Variable thickness and lithology.
2. Murchison Bay Formation. c.10,000ft.
   Dolomites and limestones; slates, quartzites: carbonate rocks in the upper, arenaceous rocks in the lower part. Further subdivided into 6 series.
1. Cape Hansteen Formation. Porphyry and agglomerates, tuffs, and resorted products of these. Considerable, but not accurately known thickness.
   BASE NOT EXPOSED.

Above the volcanics of the Cape Hansteen formation lies a total thickness of about 13,000ft. of sediments, the topmost portion of which contains primitive Cambrian brachiopods.

This succession of rocks will be discussed with a view to discovering the pattern of development of geological conditions in the eastern zone.

1. CAPE HANSTEEN FORMATION.

The oldest rocks consist dominantly of grey-green or green porphyry, with subsidiary violet to red-grey porphyry, grey quartz porphyry, green-grey quartz phyllites - mostly of more or less rearranged pyroclastic material - agglomerates, and conglomerate. Thus mainly intermediate extrusive rocks are interbedded with agglomerates and tuffs. Quartz porphyries, sometimes demonstrably cutting the intermediate types, occur as beds, or thin sills. The basic rocks, occurring abundantly in the country east of Wijdefjorden (Blomstrand, 1864) may represent a basic phase of this vulcanicity.

In the area around Gerardodden, at the head of Lady Franklinfjorden, the junction between the Cape Hansteen formation, and the Murchison Bay formation has been examined, but the ground is not well exposed, and the structure makes interpretation difficult. Kulling observed no well defined bfeak between the fine-grained tuffs, and the quartzose sandstones which here form an infold of rocks, taken on lithological similarity to be the base of the Murchison Bay formation. The ill-defined line of junction was interpreted in the field as a zone in which material from the upper portions of the Cape Hansteen formation had been resorted: no basal

conglomerate was found. Kulling believes that the two series are probably conformable but reservedly remarks that the zone between the typical Cape Hansteen volcanic rocks and the quartzites of the Murchison Bay formation could represent a small or large interval of time.

Conditions during the formation of the Cape Hansteen formation are difficult to infer from the descriptions, and Kulling does not state his views on whether the volcanics are of marine or subaerial origin. The presence of interbedded pyroclastics, and the fact that they apparently grade upwards through fine grained tuffs to more pure, terrestrially derived sediments, as has just been described, suggest submarine extrusion.

2. MURCHISON BAY FORMATION.

Very roughly 10,000ft. thick, the Murchison Bay formation, follows the Cape Hansteen formation, and has been subdivided thus :-

6. Rysso Series: 2,100ft. to 3,500ft. The characteristic rock is the light grey Rysso dolomite, oolitic and stromatolitic, dominant in the middle and lower portions of the series: there also occur dark dolomites and dolomitic limestones, chert horizons, and some slates and mudstones.

5. Hunnberg Series: 1,300 to 2,000ft. Grey and dark grey limestone, and dolomitic-limestone are typical. The central part of the series is lighter in colour, with grey or buff limestones, as well as subordinate red-brown limestone, and brown shale. Horizons of chert concretions, chert conglomerates, and phosphorite concretions also occur.

4. Salodd Series: 600ft. to 850ft. Green-grey dolomitic siltstone, with dense impure quartzite, dolomitic slate, and dolomite.

3. Raudstup Series: 2,000 to 1,450ft. Red-brown and green-grey shale, partly with carbonates, partly sandy: horizons of white quartzose sandstone.

2. Norvik Series: c.1150ft. Green-grey to grey sandstones and slaty sandstones dominate: white quartzite, dark grey muddy sandstone and calcareous sandstone also occur.

1. Flora Series. 2,050ft. White, pink, and some grey-green quartzose sandstone.

(CAPE HANSTEEN FORMATION BELOW).

In this great thickness of sediments a continuous change of lithology can be made out, from the sandstones at the base, through shales, to carbonate rocks in the upper parts.

The Flora Series consists mainly of pure quartz sandstone, of even grain and with no trace of conglomerate. The often quite pronounced red colour indicates some kind of oxidating conditions during deposition, but the sandstone is not a 'terrestrial 'Old Red' facies type, but a basal sandstone, well washed, and probably formed close to a low lying borderland. The darker colour of the succeeding Norvik Sandstones, the mud films on the bedding planes, and the shale bands show that in this period considerably more mud was brought into this part of the deposition area. The sandstone is dominantly green or grey, perhaps - according to Kulling's view - indicating a climatic change.

In the Raudstup Series which follows, the shale facies is completely dominant, although horizons of white quartzose sandstone occur, and some of the shale bands are very calcareous. The colour is alternately red-brown and grey-green.

The dominant colour in the Salodd Series above is again grey-green, and conditions seem to have returned to those of the Norvik period in that the sandstones of the two are very similar; but the mud component is less marked here. Instead, a considerable amount of dolomite occurs, and silica is present which has been chemically precipitated. Quite pure bands of dolomite are present in the series.

The Hunnberg Series shows evidence of different conditions. Dark coloured, and partly bituminous limestones and dolomitic limestones indicate rich organic life in the basin of sedimentation: this conclusion is corroborated by phosphorite concretions in the middle parts of the series, and by the occurrence of stromatolites - of Gymnosolon type. The terrigenous mud is only a minor component in the series, mainly restricted to thin, sporadic shale bands. The (primary) dolomitic component of the carbonaceous rock is fairly considerable, and narrow horizons of lighter coloured dolomite, occur subordinately.

In the succeeding lower and middle parts of the Rysso Series in which Rysso dolomite is dominant, the dark colour does not reappear as the formation of pure dolomite continued,

bituminous types being completely absent. Stromatolite and oolite structures are characteristic, and cherty bands are fairly common. Higher in the Rysso Series dark dolomites and limestones reappear, followed by dolomite, and then by thick shales and marls (dolomitic mudstones). The mud component is thus again increasing to predominate in the upper part, indicating perhaps that the previously negative tendency of the basin has been checked - or that the borderland has risen: but the lithological facts could equally be explained as a result of climatic changes, perhaps associated with increasing relief in the area of supply; the limestones are in any case of shallow water origin. The topmost part of the Rysso Series consists of another quite thin, dolomite, indicating a further break in the supply of land derived sediment.

The whole cycle of sedimentation suggests deposition in shallow water with the prevalence of intense chemical activity in both the weathering zone, and the area of deposition. The basal 3,000ft. of land derived sandstones are well sorted, and were laid down in shallow water, sedimentation keeping pace with the sinking of the floor of the basin of sedimentation. The shale facies of the succeeding 1,200ft. may represent an important deepening of water, together perhaps with a marked transgression over the area of supply. However it might alternatively be interpreted as

evidence of decreased relief in the supply area, with a consequent lessening in the power of the agents of denudation and transport. Indeed the return to sandstone facies in the Salodd Series interbedded with shales and limestones, suggests, not a rapid oscillation between positive and negative movements of the floor of the basin, but rather a variation in the nature of supply, reflecting changing conditions in the area of denudation. Relief was reduced as erosion provided the materials for the thick basal sandstones, but rejuvenation probably followed the deposition of the Randstup shales, the Salodd sandstones again tending to become more and more fine-grained. At this point deposits formed within the basin of sedimentation itself, begin their rise to dominance in the upper 5,000ft. of the succession. The carbonate material was for the most part primarily dolomitic, and its origin lies largely in chemical precipitation, although parts are markedly stromatolitic. Beds of chert, and chert-conglomerate, indicate the presence of colloidal silica in the basin of deposition, and phosphorite nodules give further evidence of the strong chemical activity. The frequently oolitic structure of the dolomite indicates crystallisation of successive carbonate zones around a nucleus which was being rolled, in shallow water. The presence of 'oolitoids' which seem from Kullings description to be fragmentary secondary limestones - the fragments being composed of oolitic limestone - further corroborates the suggestion of shallow

water, earlier deposits being now and then broken up and redeposited.

3. SVEANOR FORMATION.

The Sveanor formation is very variable, both in its thickness and in its stratigraphy. In the neighbourhood of the type area at Sveanor in North-East Land a few measurements have been made, varying from 230ft. to 490ft. The tillites are typically grey or red-brown in colour, the grain-size of the matrix being from 'sand' to 'shale', enclosing a variety of angular fragments and striated boulders. The succession near Sveanor is detailed below :-

Grey, black, and red-brown shales.
26ft. grey dolomite, yellow-weathering.
50ft. grey tillite: grey laminated shales with numerous striated boulders.
30ft. red-brown to grey tillite: sandstone with small boulders and fragments.
66ft. grey tillite: laminated shales - numerous striated boulders.
30ft. red-brown tillite: slightly phyllitic shale - in some horizons abundant boulders.
130ft. green-grey tillite: sandstone with numerous boulders.
200ft. light grey sandstone, similar to the matrix of the tillites above.
Narrow dolomite horizon.
Shales and marly sandstones.

The fragments are mostly of light and dark dolomites, often showing oolitic and stromatolitic structures, - and are clearly derived from the upper parts of the Murchison Bay formation. No representatives of at least the lower

three divisions of the Murchison Bay formation are seen, and the presence of material from the Humberg series is not proved as the dark limestone fragments could just as well be ascribed to the higher Rysso series. East of Sparreneset about 90% of the boulder material in the tillites consists of dolomite from the Murchison Bay formation: the rest consists of some slaty rocks, but largely of igneous material including pink granophyre, granite-porphyry and aplite, grey medium-grained granite, micro-poikilitic porphyry, quartz-felsite-porphyry, syenite, keratophyre and a series of intermediate to basic surface volcanics of trachytic and ophitic texture, trachyte, spilite, amygdaloidal basalt etc., Basic tuffs are also represented, but there is no gneiss or coarse-grained granite. The granite-porphyry, granophyre and aplite seem to represent hypabyssal intrusive bodies. Most of the boulders, however, consist of surface volcanics: the hypabyssal rocks are less numerous and the grey granites are entirely subordinate.

The tillites where examined in detail have proved to be conformable with both the underlying and overlying rocks. Indeed the lower parts of the formation are often more of the nature of calcareous sandstones, without any large fragments. Varved marls at Detterbukta, occur in a stratigraphically equivalent position, but the lamination seems to be due rather to variation in the amount of iron oxide colouring, than to varying grain size or the amount of mud.

The deposits have clearly been laid down in water, conformably above the Rysso series, without any major movement of the sea floor in this area (Hinlopenstredet). The outcrops of the source area clearly included igneous rocks, but the material brought into the basin by the ice was mostly removed from the top of the preceeding formation. Uplift in some part or parts of the basin was bringing the sediments into the range of glacial action (above sea level, or within the depth limits of ice-scour) and providing the material for the Svenor formation. The prevalence of dolomite in the tillites may be a somewhat local feature - and the source area probably consisted of a wide variety of rocks. The preponderance of basic and intermediate extrusives in the igneous material may reflect widespread erosion of the Cape Hansteen formation, or may be due to the persistence of this rock type through conditions which would break down fragments of acid rocks, such as the coarser granites or granite gneisses of Archaean age. It is alternatively possible that the basic volcanic fragments were derived from extrusives lying above, or broadly contemporaneous with, the Rysso dolomites, occurring in the area of glacial erosion, but not reaching this area. This would certainly help to explain the notable absence of material derived from rocks between the Rysso series and the Cape Hansteen formation, particularly the hard massive quartzose sandstones of the lower part of the Murchison Bay formation,

which might have been expected to occur in abundance if erosion had cut through to the level of the Cape Hansteen formation.

The Sveanor period, then, shows in this area a continuation in the disposition of the basin from Rysso times, though a considerable time gap may be inferred. The source area, however had risen, and sediments of the basin, just previously formed, were brought into the sphere of glacial erosion to provide the dominant boulder material of the tillites

4. CAPE SPARRE FORMATION.

In detail the stratigraphy is as follows :-

7. Upper dolomite series. ~~ft. to ft.~~ 460ft. to 660ft.
   At Sparreneset 130ft. of dark grey to black dolomitic mudstone with trail marks and brachiopods, lie above two or three hundred feet of grey dolomite.
6. Upper quartzite series. 360ft.
   Variegated quartzose sandstones and slaty sandstones: some dolomitic mudstone.
5. Upper shale series. 425 to 460ft.
   Shales and laminated dolomites with streaks of chert: the shales are green-grey and pink.
4. Middle quartzite series. Thin.
   White and red-grey quartzose sandstone.
3. Lower dolomite series. 390ft.
   Dark grey and black dolomites and dolomitic limestones.
2. Lower quartzite series. 100 to 130ft.
   White quartzose sandstone - badly exposed.
1. Lower shale series. 820ft.
   Grey-green and red-brown shales and marly mudstones. At the base is a narrow horizon, 30ft., of hard dolomite.

SVEANOR FORMATION.

The total thickness is thus roughly 2600 or 2800ft.

Fossils are known from only the topmost horizon, but exposures are poor in this area, and further study may yield fossils from lower beds in the Series.

The thick basal shales probably represent post glacial mud, above the narrow dolomite which immediately follows the Sveanor tillites. It is interesting to note the formation of dolomite immediately after glaciation and, on S.Russoya, possibly contemporaneously with the tillite. The muds were presumably deposited as the glaciated area rose during the retreat and melting of the ice. The succeeding quartzose sandstone may indicate shallowing, but the thickness of this and the succeeding dolomites - which are all probably shallow water deposits - indicate that the floor of the basin was continuing to subside steadily. Land derived material again comes into dominance in numbers 4, 5 and 6 of the scheme overleaf - another rejuvenation of the source area is indicated. Mud cracks and ripple marks on the surface of the quartzose shale indicate that the sea floor rose at times to around sea level. Deepening presumably occurred as the thick upper dolomite series was formed, the supply of land derived material having once more become a minor factor.

At this point the fossil evidence fixes the age of the beds as Cambrian. The inarticulate brachiopods found are mainly of the Lingulella and Obolus types, - and include Lingulella sp., indicating fairly definitely a lower Cambrian age. Fucoids and trail marks are also common, including

marks of some Helminthoidichnites and Planolites types.

The succeeding rocks have all been eroded and no further direct evidence of the history of this part of Spitsbergen is available, until the major Caledonian folding began.

The other stratigraphical accounts dealing with rocks in the eastern and central zones comprise the work of Sandford in North-East Land (1925,1950): and Blomstrand (1864), Fleming and Edmunds (1941), Fairbairn (1933), Odell (1927), and Harland (1941) in Ny Friesland.

Further to the east than Kulling's type area, in the region of Rijps Bay and Cape Platen, Sandford (1950) has worked out a succession from the field notes made by Glen in 1935-6. The rocks are exposed in a broad open syncline occupying Loven Peninsula, the axis plunging to the S.S.W. The succession in the west limb is not identical with that in the east limb, and Sandford compares the two sections :-

The West Limb.		Thickness in ft.
9.	Black shales.	
8.	Grey dolomites with greenish shales, soft quartzose beds, and quartzites.	165
7.	Quartzite series (White and yellow quartzites-ripple and surface marks) (Massive grey quartzites.) (Thick and massive white & purple quartzite.)	920

6.	Grey black shales.	130
5.	Flaggy quartzose sandstones with ripple marks and surface marks.	560
4.	Shales interbedded with quartz sandstones.	130
3.	Black and grey slates or shales, and fine-grained grey quartzites.	230
2.	Black and grey slates or shales, and fine-grained grey quartzites.	130
1.	Porphyry and black shales with veins of red granite in the lower part.	?
	Grey granite etc., veined with red granite.	

The East Limb.

9.	Black and grey shales with siltstones.	?
8.	Gap.	
7.	Quartzite series (Yellow, pink & green quartzites, 560ft. / Grey quartzose sandstone 50ft. / Red sandstone, 33ft.)	c.650
6.	Grey black shales.	180
5.	Quartzites with red sandstones, some dolomite and white quartzites.	855.
4.	Alternating beds of green, grey, brown, purple and yellow shales.	410
3.	Grey to white quartzites, with 33ft. black shale band.	c.130?
2.	Interbedded siltstones and black shales and quartzites.	?
1.	Black shales and phyllites.	?
	Red granite.	

Certain discrepancies are seen, particularly in the thicknesses; some of these, however, (for example numbers 5 to 8 of the East limb) had to be calculated from width of outcrop assuming an average dip (40°). The importance of the differences in lithological details is difficult to estimate: in view of the practical difficulties of observation it might be unwise to infer any variations of conditions over this area as such. It is, however, of value to compare the succession and thicknesses with those of the Murchisonfjorden area.

Sandford considers that beds 1 and 2, above, probably represent the top of the Cape Hanskeen formation. The 2,000ft. of quartzites with shales of beds 3 to 7 are the Flora Series, and beds 8-9 probably belong to the Norvik Series. Perhaps the most important point is to compare the Flora Series here with the rocks 40 miles to the west. The thickness is very similar - around 2,000ft. Lithologically the important difference is the occurrence here of a fair proportion of shale in the series, - beds 4 and 6, whereas in Murchisonfjorden the rocks are all quartzose sandstones.

The sandstones of the Loven Peninsula were obviously deposited in shallow water; ripple marks and suncracks occur at several horizons. Impressions of algal type and trail marks occur on some of the ripplemarked bedding planes of the Flora Series - a feature not noted in the type area.

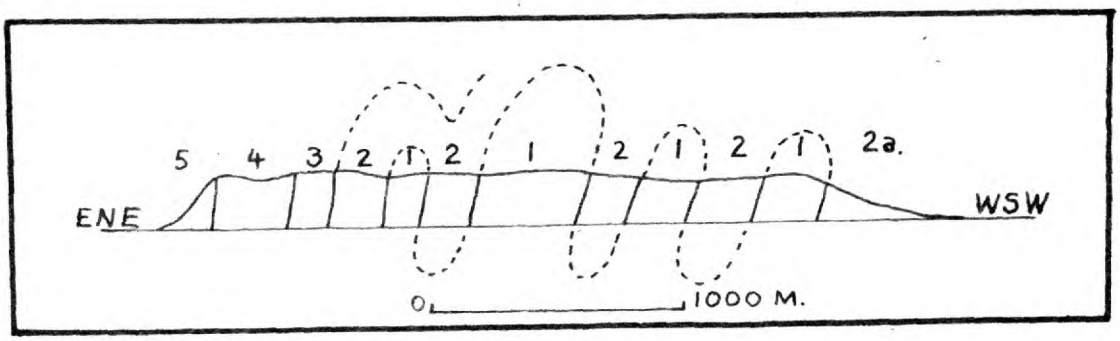
Further east than the Loven Peninsula, on Rijps Peninsula itself, the geology is less well known. Sandford believes that the Cape Hansteen formation lies unconformably above the older red and grey granites and gneisses which outcrop to the east, and most of the sediments are of the Flora Series, little or no more of the succession being represented.

Structurally it is important to note the marked contrast between the open synclines and anticlines of this area, and the tight folds of Murchisonfjorden, sometimes isoclinal and overturned to the east. The degree of shortening due to folding thus decreases rapidly as the beds are followed eastward.

D I A G R A M 2 6 .

Section, across strike, through S. shore of Fsxevika on N. shore of Lomfjorden.

5. Hunnberg Series. 4-3, Selodd & Rendstup Series.
2. Norvik Series. 2a, possibly Norvik Series. 1. Flora Series.



Work in My Friesland.

Turning now to rocks in, and on the flanks of the central zone, we find that successions are more fragmentary than Kulling's, due to the complications of intense, isoclinal folding, and medium to high-grade metamorphism and granitisation. Blomstrand and Nordenskjold in 1861, and Fleming and Edmunds in 1933, worked in the northern part of New Friesland, respectively west and east of the central core of gneiss which separates the sediments of the peninsula into two provinces. Odell in 1921 and 1923 also worked in the eastern part, to the south of Fleming and Edmunds' area. More recently W.B. Harland has studied the high grade Hecla Hoek rocks of the Stubendorff mountains - 1939 - and extended that work northward in the summers of 1949 and 1951, also linking up his observations eastward to those of Fairbairn (1933), and to Odell's area.

KULLING visited the districts of Lomfjorden and Sorgfjorden briefly in 1931, to discover if the stratigraphical divisions he had worked out in North East Land could be applied. His mapping in Lomfjorden, and his section, reproduced opposite, indicate that the rocks can bedirectly correlated to the type succession.

Elsewhere, on the east shore of the fjord, and on an island east of Faxevika, there is clear evidence that the highest beds shown in the section above are followed (further to the east) by the Rysso Series - with typical Rysso dolomites. Members of every part of the Murchison Bay Formation are thus recognised here, and the structure is interpreted as consisting of tight isoclinal folds whose axial planes dip slightly north of east.

Kulling describes the section as follows :-

A.	500 or 600ft. dark grey limestone and dolomitic limestone.		Hunnéberg Series.
B.	65ft. gap. 920ft. grey green slatey quartzite, and dolomite.	1500ft.	Salodd and Randstup Series.
C.	325ft. gap. 160ft. grey-green shale.		
D. F. H. J.	Dark grey slaty quartzites with quartzite and phyllite bands. Quartzite often laminated.		Norvik Series.
E. G1. K.	Thick bedded grey, grey-green, or red-brown quartzites (with one 30ft. band of dark phyllite in E).		Flora Series.

It is difficult to infer very much from these observations, as to lateral facies changes in the Murchison Bay Formation. In general the thicknesses are less than in North East Land, the Salodd and Randstup series together totalling 1,500ft. as opposed to 1,800 to 2,000ft. in the type area : the Norvik series is apparently 700ft. thick here,

1150ft. in Murchisonfjorden. It would be unwise, despite this, to be certain that these differences are due to original variation in the thickness of the beds, and not to repetition by folding on the one hand and tectonic thinning on the other; or even to the difficulties and sparsity of observation in these districts with their extensive ice cover.

In the area around Sorgfjorden the rocks are again of similar lithology to those of the type section, but Kulling's study was essentially confined to a traverse across the strike in the region of Hecla Hoekfjellet, east of the fjord. His observations and interpretations are given below, horizons outcropping from W. to E. as follows. No accurate estimates of thicknesses are available.

Hunnberg Series.	(K1. White crystalline limestone. (K2. Narrow horizon of grey dolomite. (K3. Dark grey, phyllitic limestone.
Salodd, Raudstup, ?Norvik Series.	(K4. Grey and grey-green slate, and grey dolomitic slate. (K5. Grey-black shale.
Flora Series.	(K6. Hard pink quartzite. (K7. Grey, finely bedded quartzite. (K8. Light grey quartzite. (K9. Pink quartzite.
Norvik Series.	(K10. Dark grey finely bedded quartzite series with frequent shale films. (K11. Grey green to light grey dense, slaty quartzite.
Salodd Series.	(K12. Yellow-weathering grey slates, dolomitic slates, and dolomites.

Hunnberg Series.	(K13. Grey calc, phyllites and phyllitic limestones.
	(K14. Grey phyllites, and darker phyllitic limestones: oolitic
Flora Series.	(K15. White and pink quartzites.
Norvik Series.	(K16. Grey-green slaty quartzites; subordinate white quartzites; ~~subordinate-white~~ quartzites.
Raudstup Series.	(K17. Dark violet and pale green shales; some carbonaceous.
Norvik. Series.	(K18. Dark grey quartzites and slates.

The standard stratigraphic scheme is thus, to some extent corroborated, but fairly considerable tectonic disturbance has to be invoked, and thicknesses are not forthcoming.

FLEMING and EDMUNDS (1941) work to the south and west of Sorgfjorden is much more useful in this respect.

In the Syd range and to the east and north-east of it, the succession of rocks exposed is as follows :-

4. Thin series of dark sandstones, with some dark grey laminated shale bands.

3. (320ft). 200ft. of light coloured (pinkish) quartzites overlie 120ft. of even bedded white, pink and green quartzites.

2. (300ft). Grey sandstones with thin bedded, laminated black shales rarely more than 3" thick. Considerable tectonic contortion.

1. (Over 300ft.) Pink and light grey quartzites interbedded with very thin shale bands and lenticles, in places phyllitic ? ripple marking in the quartzites.

The massive brightly coloured quartzites of 1 and 3 are attributed to the Flora Series, and 2 is assumed to be an infold of the Norvik series, with its greater proportion of shaley material within dark sandstones and thin-bedded quartzites. The thickness, slightly more than 300ft. is vastly different from the figure of over 2,000ft. which Kulling gives for the Flora Series of Murchisonfjorden, and it seems to the present writer more probable that the whole 900ft. of quartzites represented by 1, 2 and 3, belong to the Flora Series. The evidence is too uncertain to justify any really definite conclusions.

The Syd quartzites contain shale lenticles and thin bands, some of which are phyllitic. In this they differ from the Flora quartzites of the type area, but resemble the facies developed at Faxevika.

To the east of the Syd Glacier, the quartzites again appear, predominantly red, but with green and white members. They are of characteristic 'Flora' type, and demonstrate that the series despite the prevalent high dips, is repeated at the surface over quite a large horizontal distance, due to the isoclinal folding.

Continuing eastward the quartzites give way to laminated shales and dark quartzites of 'Norvik' type, associated to the east with yellow, well banded, siltstones and mudstones. The next part of the succession is detailed below:-

Laminated shales - weathering yellow green.)
Green and purple cleaved slates.) Sveanor
Purple cleaved slates with granitic pebbles) Formation.
and fragments.)

12. 20ft. Light calcareous conglomerate, and lime cemented oolite.
11. 350ft. Pale grey and white banded limestone.
10. 100ft. Grey massive limestone.
9. 120ft. - yellow green, banded, flaggy siltstones.
8. 500ft. White massive limestone and dolomite with cherty limestones.
7. 120ft. Dark grey limestone.
6. 200ft. Light grey massive limestone, with banded grey limestone.
5. 220ft. Black shaly limestone.
4. 60ft. Grey limestone.
3. 250ft. Black shaly limestone and dark grey limestone.
2. 450ft. Grey limestones and dolomites.
1. 300ft. - Dark shales.

This limestone series comprises a diverse and interesting group of sediments, which include, - besides more normal dolomites and limestones - cherty limestones, calcareous sandstones, and limestone breccias in which angular fragments of porcellanous limestone are cemented in a dark matrix of coarsely crystalline calcite.

Towards the top, not far below the Sveanor formation calcareous sandstones are developed. These show rounded quartz grains up to $^{3}/_{16}$ inch in diameter, with small amounts of felspar - mostly oligoclase, some microcline: a little detrital tourmaline and rutile is present; the calcite occurs as a fine matrix but sometimes also as rounded grains. The larger particles of quartz, though much recrystallisation has occurred, often show that they are fragments of a pre-existing, finer-grained, cemented sandstone or quartzite. These are

therefore, at least partly, second cycle quartzites or sandstones.

The calcareous and dolomitic rocks of Gorge Valley reach a thickness of roughly 2,400ft. They evidently correspond to the Hunnberg and Rysso Series - but do not reach the thickness of 4,000ft. seen in the type area. Fleming and Edmunds believe that the upper parts of the Rysso Series are absent here, partly because they failed to find any large development of the characteristic Rysso-dolomite facies here.

The least certain part of the correlation is the precise identification of the members of the Salodd and Raudstup Series. The 300ft. of dark shales below the limestone series is separated from the Norvik Series here by a large gap in the observations.

The fine grained slates above the limestones, are unquestionably the Sveanor formation. The slates are of two colours, a purple group is overlain by a green group - the latter with segregations of fine purple coloured material. Both groups are fissile fine-grained slates. The purple group below contains pebbles of and boulders of granite (pink) up to 1 or 2ft. in diameter, which are well rounded and much weathered. They have an irregular distribution, and appear to have sunk into the soft fine material from above. The series is conformable with the limestone series and is clearly a tillite deposited in water.

The boulder material, the source of which is not known, is in marked contrast to that in the type locality at Sveanor, where dolomitic and volcanic fragments are almost exclusively found. This is not very surprising for if the deposit is accepted as a marine tillite, it would be expected that the boulder material should vary somewhat from one locality to another, and also that the beds should be found to rest on various horizons of the Rysso series - or even older rocks - at different places. Here in Gorge Valley, Fleming and Edmunds believe that the upper part of the Rysso Series is missing, and that its erosion may have provided material for the deposit at Sveanor to the east. The Sveanor tillites are presumably diachronous, though within a definite, and fairly narrow, time-range.

Fleming and Edmunds also worked out a succession in the Rosen Mountains (see Map Diag 25 ~ p.147. which corresponds very closely to the observations made by Kulling on the west side of Sorgfjorden, - about 10 miles north, and directly along the strike. The two successions are set out below :-

West.	West side of Duner Glacier (F & E).	West side Treurenberg Bay (K)
	Garnetiferous mica-schists. Light quartzites.	Light coloured mica quartzites.
	Green chloritic schists.	Grey phyllitic mica schists.
	Dark coloured limestones.	Grey marble (The 'solitary layer').
	Green schists or phyllites.	Grey phyllitic mica schist & mica quartz phyllite(NORVIK)

Light coloured quartzites. White to pink quartzites (FLORA) East.

The light coloured quartzites are principally pink, and resemble the Syd quartzites. The green quartz-mica phyllites and schists which follow, Kulling identifies as the Norvik Series. 200ft. of limestones follow at the Duner Glacier, after a zone of 16ft. in which limestone alternates with schist. Beyond this, and to the west, green-grey phyllitic schists follow the limestone, similar to the rocks east of it. The further fact that light coloured quartzites occur west of these, suggests the possibility that structural complications may be involved, the limestone occupying the centre of an isoclinal syncline.

The occurrence of a dark coloured limestone lying immediately and, apparently, conformably above the Norvik Series is of interest, when this is compared with the sequence at Murchisonfjorden, where over 900ft. of the Raudstup and Salodd Series separate the Norvik Series from the first carbonate rocks of the Murchison Bay Formation. This point is discussed later when a more general discussion of the various correlations is undertaken.

Work by Fleming and Edmunds at the head of Gullfaxe Glacier yielded the apparent succession :-

WEST.

10. Gneiss with felspar porphyroblasts.
9. 100ft. Massive pink and white quartzites.
8. 100ft. Green schists with thin dark quartzites at eastern end.
7. c.200ft. Gneiss with pink felspar porphyroblasts - similar to 10.
6. c.100ft. Banded green quartzose schists interbedded with thin dark quartzites.
5. 200ft. Massive, and fine banded red quartzites.
4. 300ft. Banded quartzites with green schists and banded quartz schist.
3. 50ft. Compact quartz-mica-schist.
2. 100ft. Green schists and banded quartz-schist.
1. 550ft. Yellow green and red quartzites, rather thinly bedded.

EAST.

No discordance between any of the beds was observed, but it was noted that they fall into three classes, which are repeated :- thus 1, 5 and 9 are light coloured, mainly pink and white, quartzites; 2,3,4,6 and 8 are green schists, phyllites, and quartz-schists with some thinly bedded dark coloured quartzites; 7 and 10 are gneisses, apparently identical petrologically, The light coloured quartzites are taken to represent the Flora series : they closely resemble the Syd quartzites. The phyllites and quartz schists of numbers 2,3,4,6 and 8 are identified as the Norvik Series. A great amount of isoclinal folding must have occurred if these identifications are correct, but such seems not unreasonable from a consideration of the regional structure.

ODELL'S work in 1921 and 1923 was carried out about 25 miles further to the S., but very close to the area in Lomfjorden where Kulling was able, in 1931 to recognise the stratigraphical units he had proposed for Murchisonfjorden. Odell's succession is as follows : he divided the rocks into two series :-

Upper Series:-

7. Cherty conglomerate.
6. Black and white chert horizon.
5. Pale and dark dolomites and limestones of great thickness, including an intraformational conglomerate and an horizon of oolite and oolitoid Rysso-dolomite.
4. Red shales with thin quartzites and quartzose slates.

Lower Series:-

3. Dark dolomitic limestones and pink and grey streaked marbles.
2. Dark laminated shales or siltstones, hard buff coloured and blue slates, often spotted and interbedded with pink quartzite.
1. Purple massive quartzite)
   Pink massive quartzite) About 1,000ft. exposed.
   Yellow massive quartzite)

Odell suggests that the thickness may exceed 32,000ft: in the neighbourhood of the Bear Bay Glacier the upper series alone seems to reach 10,000ft. The evidence is however, admitted to be far from conclusive, Kulling suggests that in view of the complicated tectonics, which Odell makes no claim to have worked out in detail, the thicknesses have been very much over-estimated, particularly as the style of folding is isoclinal.

The correlation is otherwise good. Number 1, the

massive quartzite, is the Flora Series. The thickness is only 1,000ft. but the base is not exposed and clearly only the upper part of the series has been examined. The dark laminated shales interbedded with quartzites constitute the Norvik Series, here apparently less arenaceous than in the type area. The dark dolomites above (3) do not correspond in lithology to the 1,000ft. of shales of the Randstup Series which follow the Norvik Series at Murchisonfjorden. They do however agree with the observations of Fleming and Edmunds at the Gullfaxe Glacier, and there seems some doubt as to the correctness of Kullings views on the classification of this part of the Murchison Bay formation. Kulling maintains his standard sequence despite this, and suggests that Odell has misinterpreted the stratigraphy, and that the positions of 3 and 4 may in fact be the reverse, that is to say, that the red shales of 4 lie above 2 and are followed by the dolomitic limestones 3.

The next series, number 5, must correspond for the most part to the Rysso Series, with the typical Rysso-dolomite lithology, although the uppermost shale beds of the Series are not present here. Probably the chert horizons, which come at the top of Odell's succession are the same as those occurring in the central portions of the Rysso Series of the type area.

The section, then, extends from a point above the base of the Flora Series, to about the middle of the Rysso Series.

These two distinctive series, and the Norvik Series, can be recognised clearly but the relation between the beds which lie between the Norvik Series and the Rysso Series in this area, and in the type area, is less clear. Kulling believes that the standard succession applies at Lomfjorden and on the east side of Sorgfjorden. Fleming and Edmunds are unable, with their fragmentary successions, to connect the Flora and Norvik Series with the Hunnberg and Rysso series. 300ft. of dark shales, following the Norvik Series in the Rosen Mountains, could be interpreted as the base of the Randstup Series, but there is a large break in the observations above this horizon. At Gullfaxe Glacier however, limestones follow the Norvik Series. Odell's succession corroborated this last sequence, red shales following the dark limestones, and leading to the Rysso dolomites with perhaps the Hunnberg Series. The evidence is about equally strong for the two alternative views on the meaning of these observations : either that Odell has misinterpreted the stratigraphical sequence, his series 4 being the Randstup and Salodd Series, and series 3 the Hunnberg Series : or that there is in fact a marked contrast in lithology in those parts of the Murchison Bay formation lying between the Norvik Series and the Rysso Series, over the area so far considered.

It would be pleasing to be able to draw more definite conclusions than this, but in view of the comparatively small amount of detailed work it has been possible to carry out, as

yet, in these areas, it would be most unwise to discuss, for example, apparent lateral changes in lithology which may be due equally to misinterpretation or lack of evidence, as to features of the original sedimentation.

On the western side of the central permeation zone of Ny Friesland, Blomstrands work of 1861, and the more recent Cambridge Expeditions under Harland's leadership have shown that the structure is isoclinal toward the centre, with upright axial planes running N. and S., but that towards the west, particularly in the Stubendorff Mountains, recumbent folding and thrusting with nappe structures have developed, the direction of overfolding being to the west. A detailed succession for these areas has not been published, but the descriptions by Blomstrand of the NW part of the peninsula suggests strongly that the rocks here are the lowermost quartzose divisions of the Murchison Bay formation and the underlying porphyries of the Cape Hansteen formation.

Harlands description (1941) of the Stubendorffs includes rocks of 'lower Murchison Bay formation type', and a widespread series of amphibolites. The latter have also been described by Fairbairn (1933) in his mainly petrological study to the east of the Stubendorff. These rocks are interpreted as derived from recurring flows of basalt interbedded with sediments, presumably further representations of the Cape Hansteen formation.

This Cambridge research in Ny Friesland continues,

Harland following his pre-war work with further expeditions in 1949, 1951 and 1952. Stratigraphical results cannot be expected to be easily worked out here, but the structural and petrological data are already proving most valuable in the building up of the Hecla Hoek picture.

Of the stratigraphy of the west coastal zone of the Spitsbergen Caledonides surprisingly little is known. The north-western part of the island is an area which has undergone medium to high grade regional metamorphism and granite intrusion, and the studies of Holtedahl (1926) and others have shown that it is unlikely that a very coherent succession could be made out here.

South of Kings Bay, however, the grade of metamorphism is less high and stratigraphical work has been undertaken by Holtedahl (1913) and Orvin (1934) on the mainland, and by Tyrrell on Prince Charles Foreland (1924). More recently the Birmingham University Expeditions of 1948 and 1951, have worked between St.Johns Bay and Ice Fjord, and produced a succession in marked contrast to those proposed by previous workers, but to some extent similar to the one worked out by the present writer on Prince Charles Foreland.

The belt of Hecla Hoek rocks continues along the coast south of Ice Fjord, but little has been written of their detailed stratigraphy : what has been published will be dealt with before a discussion of the Hecla Hoek north of Ice Fjord is begun.

Orvin has mapped the greater part of the area between Bellsund and Hornsund, and a large amount of work, as yet unpublished, has been partly written up in Oslo. Strong folding, thrusting and faulting have however prevented the elucidation of the original succession of beds. The sedimentary rock types present are limestones, dolomites, slates and phyllites, quartzites and conglomerates. Two horizons with thick conglomerates evidently represent large breaks in deposition. One of them resembles morainic material, but Orvin is not certain that it represents a tillite horizon. Fossils are entirely absent, except perhaps for a "tube-like fragment" found in a partly dolomitised limestone on the east side of Gashamna in Hornsund. It is, according to Orvin, "certainly a fossil, probably a crinoid stem". These limestones are thus younger than PreCambrian, and most probably Ordovician : They are, according to Orvin, very similar to the Tetredium limestones of Bear Island, but he hesitates to identify them without better fossil evidence.

The stratigraphy of the Hecla Hoek formation on Prince Charles Foreland has been described in considerable detail in Chapter II. It remains to consider how it fits the stratigraphical data from the rest of Spitsbergen, which has been dealt with in the present chapter.

Prince Charles Foreland unfortunately has no Archaean basement, no volcanic series, no tillite and no fossils. An immediate firm correlation with the succession around Hinlopenstredet cannot therefore be effected. On the Foreland there are essentially two coherent series of stratigraphical groups - the main sequence of the northern division, and the Gordon-Geikie-Ferrier sequence in the south; as well as numerous further groups whose sequence is uncertain. The latter are of little help in stratigraphical correlation; the detailed record of them is of immediate value only to increase our estimate of the minimum thickness of the Hecla Hoek formation on the island. This figure is approximately 46,000 ft.; the coherent northern succession amounting to 15,000 ft., the southern to 10,000 ft.

Recrystallisation prevents the south division from telling us very much, but the northern succession broadly represents a cycle of sedimentation in which quartzites give way to slates and limestones as the cycle proceeds. The

current bedding in the quartzites and detrital limestones, the oolitic structures in the latter, the frequent evidence of disconformity, and reworking of sediments just laid down, all indicate that the rocks were deposited in shallow water. The progressive change in their composition is therefore a reflection of changes in the source area and not a result of deeper water, or positions further from the shore.

We must thus interpret the well sorted, pure Fuglehuk quartzites as indicative of strong relief and erosion in the area of supply. The variable facies developed in the Barents group suggest unstable conditions, with local rejuvenation, disconformity, and reworking of only recently formed sediments.

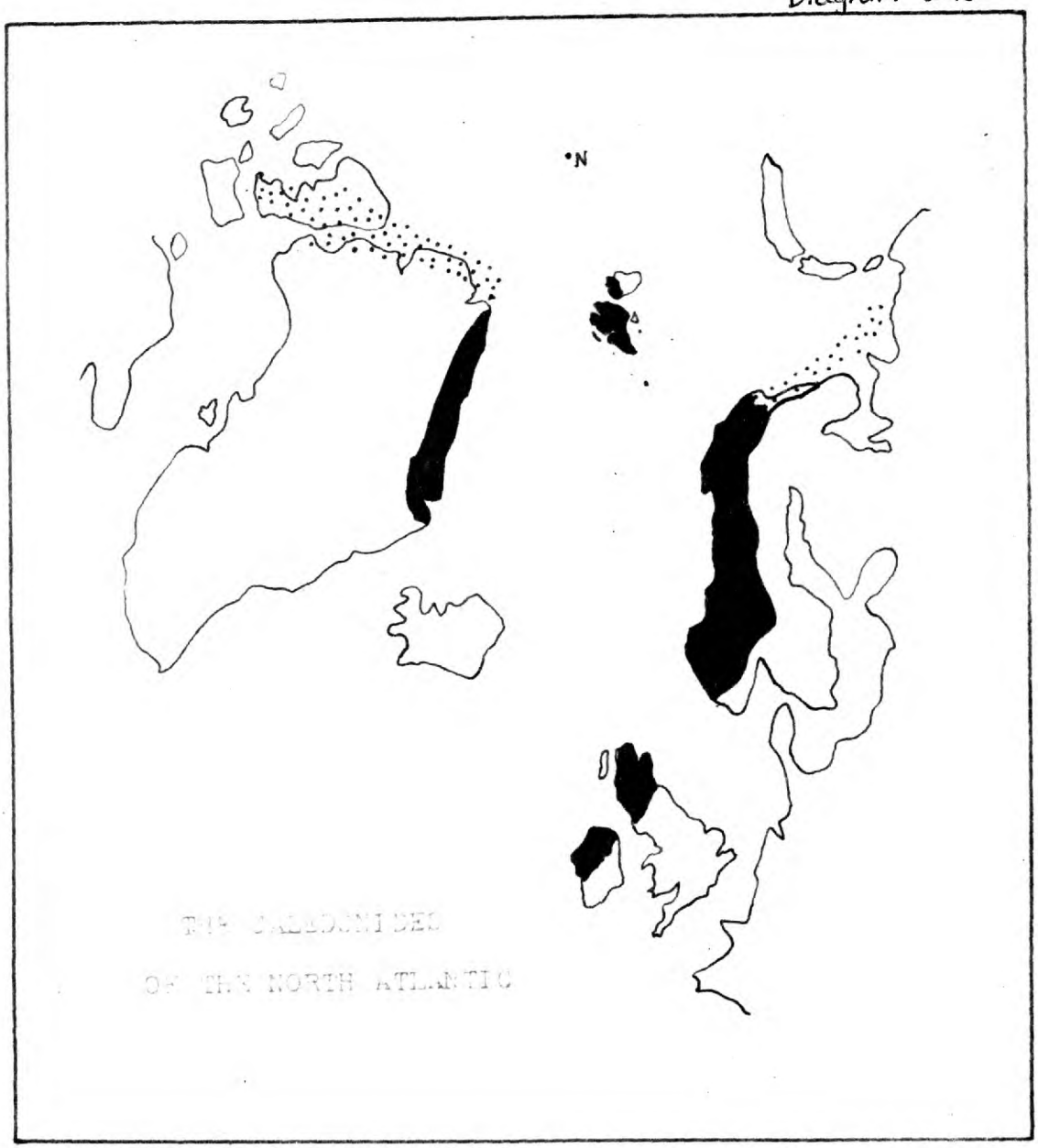
The recurrence of quartzites in the Conqueror group presumably indicates more general rejuvenation. The poor sorting and the amount of clay material may indicate rapid deposition, or feebleness in relief and consequently in transporting and sorting agencies. Shallow water, little land derived material, a great deal of precipitation of carbonates and colloidal silica, characterise the Scotia series and indicate a low lying borderland.

A parallel to this sequence is seen in the development

of the Murchison Bay formation - and for this reason it seems to the writer that <u>there</u> lies the direction of most hopeful enquiry, in correlating the rocks of the west coast with those of North-East Land. There are happy coincidences of lithology - the 'basal' quartzites (the base of the Fuglehuk group is not seen) - the succeeding, less pure, quartzite series, and the final dominance of grey and oolitic limestones, with cherts. But the distance separating the two areas makes one cautious of a correlation based on detailed coincidence rather than an overall similarity in development.

The stratigraphy of the Foreland then is, by itself, too much confused by the structural complexities, to allow one to discover its relation to the Hecla Hoek of the eastern zone of Spitsbergen. In combination with other work in the west coast zone, there seems every hope that the correlations will eventually be made. To the writer, however, it seems unlikely that the stratigraphy of the eastern and western zones will coincide in much detail : the work on the Foreland has already shewn that the Hecla Hoek formation is there much thicker than in the Hinlopenstredet area.

Diagram 27.



THE CALEDONIDES
OF THE NORTH ATLANTIC

CHAPTER VI. THE CALEDONIDES OF THE NORTH ATLANTIC - ARCTIC PROVINCE.

The Caledonian rocks of the rest of the North Atlantic-Arctic province (see diagram 27) will now be discussed with a view to showing that a common pattern of development in the geosyncline - or geosynclines - can be discerned. The rocks of Bear Island, Scandinavia, and Gt.Britain are discussed, and it is suggested finally that the stratigraphy and structure of the East Greenland fold belt support the contention that the Caledonides of the Atlantic-Arctic province provide a very strong piece of evidence in favour of Continental Drift.

BEAR ISLAND.

A.E. Nordenskjold visited Bear Island in 1864 and suggested that the dolomites and limestones of the southern part of the island were similar in age to the rocks of Hekla Mount in Spitsbergen, purely on petrological grounds - (Duner and Nordenskjold, 1867). In 1898 and 1899, J.G. Anderson devised the first interpretation of the stratigraphy of the Hecla Hoek strata, and at one horizon found fossils which included a species of Tetradium fixing the age as Ordovician (Anderson, 1900). Holtedahl spent the summer of 1918 on the island, finding further fossil horizons and arriving at a succession rather different from that of Anderson (Holtedahl, 1920-i) and ii)). In 1924-25, G.Horn and A.K. Orvin (1928) confirmed this revised succession, but showed that Holtedahl underestimated the thickness of the stratigraphical divisions. These divisions are given below, with the estimated thicknesses according to the two different investigations :-

	Holtedahl.	Horn & Orvin.
4. Tetradium Limestone Series (fossiliferous)	560ft.	790ft.
3. Younger Dolomite Series (fossils in lower part)	890ft.	1,310ft. -
2. Slate-Quartzite series	460ft.	570ft.
1. Older Dolomite Series.	1,310ft.	1,310ft.
	3,220ft.	3,980ft. -

Holtedahl did not claim that his figures were more than an approximation and tendered them as 'minimum thicknesses'. Those given by Horn and Orvin are probably nearer the true values so that at least 4,000ft. of strata of the Hecla Hoek formation are present in Bear Island.

The Older Dolomite Series, over 1,300ft. thick, is in its lower parts commonly oolitic, and there occur stromatolitic structures of Cryptozoon and Gymnosolon types. Some of the beds show subangular fragments of oolitic limestone in a non-oolitic matrix and are thus intra-formational conglomerates. The upper part of the series is more arenaceous and grades into the pure sandstones of the slate-quartzite series above - Some lime content remains however: Horn and Orvin describe one example as showing a considerable amount of partly rounded quartz grains of 0.2 to 0.5 m.m. diameter, embedded in a fine-grained ground mass of dolomite. The rocks are also oolitic locally, but not to the same extent as in the lower parts of the series. Pyrite and traces of microcline have also been noted.

No fossils have been found in the Older Dolomite Series, but Holtedahl once considered it to be contemporaneous with the Porsanger dolomite of Finmark, North Norway, which he regarded as of Ozarkian age. Foyn's detailed investigations in Finmark led him (Foyn) to conclude that the Porsanger dolomite was of Eocambrian age, and contemporaneous with the

Tanafjord dolomite, underlying Eocambrian tillites. The balance of evidence, in my opinion, favours Foyn's view. (see pp.192).

The Slate-Quartzite series is nearly 600ft. thick, consisting of red and green shales and slates with beds of quartzose sandstone. Details of the succession are not known. The slates are exceedingly fine grained, and in thin section only a few larger, angular, grains of quartz can be made out. One thin section of the sandstone shows angular quartz grains of 0.1 to 0.2 m.m., much magnetite and pyrite, and the accessories tourmaline, zircon and rutile. Another, a 'white, fine-grained sandstone', shows subangular quartz grains of 0.1 to 0.3 m.m. partly recrystallised: accessories felspar, pyrite, apatite, zircon, and sericite.

The Younger Dolomite Series has a visible thickness exceeding 1,300ft. but at no point is there exposed a continuous section down into the shale series below, and the total thickness is not known. The series consists of a uniform sequence of grey dolomitic limestones, but these often contain argillaceous material: they are not, however, arenaceous as are the Older Dolomite Series, except in a very few, thin horizons. Towards the top, beds of darker limestone occur, forerunners of the main limestone of the series above. The dolomitic limestone is a uniform rock, grey when fresh, but

weathering yellow. The grain size varies; 0.1 m.m. and 0.5 m.m. in a couple of measured examples.

Fossils (including gasteropods, sponges, crinoids and cephalopods) were found by Holtedahl in 1918 at an horizon about 820ft. below the base of the Tetradium limestone. Here the rock is of a rather different character - being fairly dark coloured and coarse enough for individual grains to be distinguished in the hand specimen. The rock contains chert-like quartz in layers and nodules, and the fossils are silicified.

The Tetradium Limestone Series, the youngest of the Hecla Hoek divisions in Bear Island, has a thickness of at least 790ft. There is a transition from the dolomites below. In detail :-

TETRADIUM LIMESTONE.

Dark grey limestone interbedded with dolomitic limestone.	60ft.
Light grey,(brown-weathering) dolomite	16ft.
Yellow weathering dolomite with thin shaly bands	7ft.
Light and dark dolomites, yellow-weathering;	20ft.
Dark grey limestone, similar to Tetr-Limestone	27ft.
Dolomitic rocks, mostly grey weathering, of the YOUNGER DOLOMITE SERIES.	

The Tetradium limestone itself is generally dark grey to black, sometimes lighter in colour. It is very fine-grained, the diameter of the grains ranging from 0.005 to 0.01 mm. The rock has in places recrystallised under stress

and shows a closely interlocking structure in thin section. Fossils are quite common, particularly at an horizon about 400ft. from the base. They include the anthozoan genus Tetradium, bryozoons, crinoids, brachiopods and cephalopods.

Dating.

The position of the Hecla Hoek rocks of Bear Island in the geological time scale, can be fixed on palaeontological grounds.

The fossils collected from the Younger Dolomite Series are detailed below:-

Sponges: Gen.Calathium Billings - (2 species as below)
Calathium cf.pannosum Billings.
Calathium cf.canadense Billings.
Archaeoscyphia (minganensis Bill.?)sp.

Crinoids: Silicified stems.

Gasteropods: - the most common fossils; usually badly preserved.
Maclurites (Maclurea) sp.
Liospira sp?
Lophospira sp?

Cephalopods: Orthoceras sp.
Piloceras cf.explanator Whitfield.

This material is very fragmentary, but it is sufficient to date the horizon, for the genera which have been identified with certainty have a very restricted distribution in time. They are from a definitely 'American' type of faunal assemblage and according to Bassler's "Index of American Ordovician and Silurian Fossils" (1915).

Calathium occurs in the Canadian, Chazy and Black River beds.
Archaeoscyphia " " " Canadian.
Piloceras " " " Ozarkian-Canadian.

This zone is therefore, without doubt, Canadian (using the N.American Stratigraphical divisions), that is of Lower Ordovician age. The essentially American affinity of the fauna is discussed later. (p.249.

The Tetradium limestone has yielded the following material:-

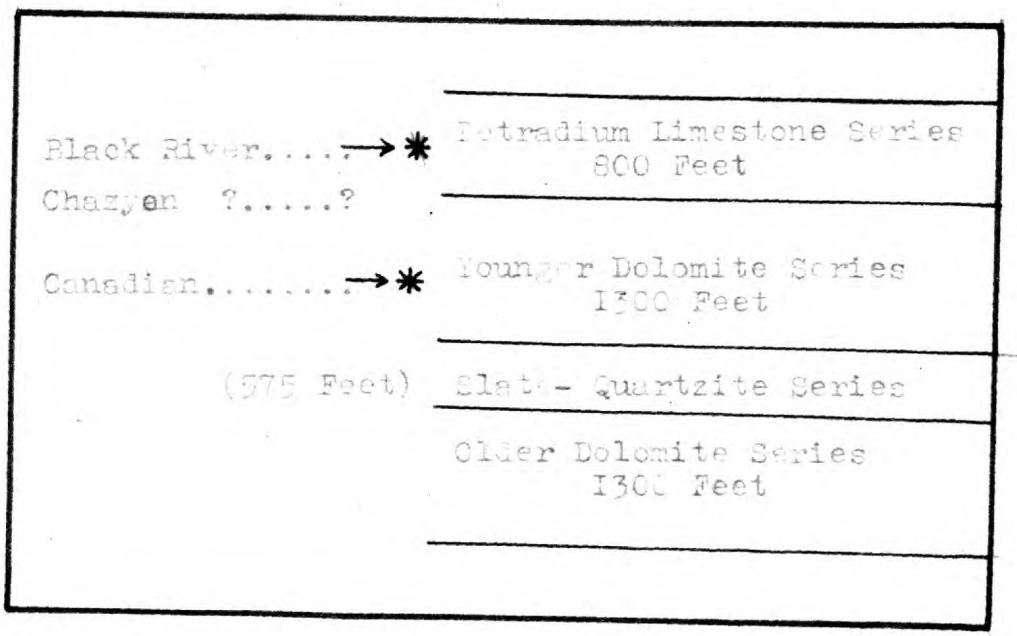
Anthozoa:- Tetradium cf.syringoporoides Ulrich (Large numbers.)
Bryozoa:- many specimens - poorly preserved.
Crinoidea:- fragmentary stems.
Brachiopoda:- Rafinesquina sp.
Cephalopoda:- Orthoceras (Kionoceras?) sp. (- sp.nov).
Endoceras (Vaginoceras?) sp.
Endoceras sp?
Actinoceras Bigsbyi Bronn - by far the most common form in the collection.
Gonioceras (occidentale Hall?) sp.

The fossils are few, and poorly preserved, but the inclusion of diagnostic forms such as Gonioceras (occidentale Hall?) sp. and Actinoceras Bigsbyi Bronn, is quite decisive evidence that the fauna is of Black River Age. It is once again of a purely American character.

Gonioceras occidentale Hall is known from the lower Black River of Wisconin and Illinois, from the Bache Peninsula, Ellesmere Land (see p.243) and from Borthia Felix and King William Land (Holtedahl,1912) in Arctic Canada.

Actinoceras Bigsbyi is a typical American species, very common in the 'Black River' over a wide area of

D I A G R A M, 2 8.


Black River.....→*
Chazyan ?.....?
Canadian.....→*
Tetradium Limestone Series
800 Feet
Younger Dolomite Series
1300 Feet
(575 Feet)
Slate - Quartzite Series
Older Dolomite Series
1300 Feet

N.America, and Arctic Canada. The Ordovician representatives of the genus Actinoceras are characteristic of the 'American' faunal provinces, but in the Silurian they spread to Europe, including the English districts, and Scandinavian-Baltic areas.

Endoceras (Vaginoceras) Hyatt is characteristic of the American Black River; but has also been recorded from the Chazy by Ruedemann.

Tetradium is also a typical American genus - common in N.America, but in Europe only recorded once, from the Baltic by Bassler, at Borkholm.

These conclusions on the age of the various series are summarised in the table opposite (diag. 18).

Structurally the rocks of Bear Island lie in the zone of W.N.W.-ward overthrusting, and are thus in a similar position, in the Caledonian orogenic belt, to the rocks of Prince Charles Foreland and the west coastal zone of Spitsbergen. This point is elaborated in the general discussion of the structure of the Caledonides.

SCANDINAVIA.

No less than five Precambrian cycles of sedimentation and orogeny have been claimed to be distinguishable in Fenno Scandinavia :-

1. Svionian.
2. Bottnian.
3. Karelidian.
4. Jottnian.
5. Sparagmitian.

The true 'Caledonian' sediments are those younger than the Jottnian and, of course older than Devonian. However, a few remarks should first be made on the Jotthian sediments, which occupy a somewhat similar position to the Torridonian of Scotland. The two formations have in fact been correlated with one another by several authors, but the amount of evidence is usually less than the desire for an anchor on which to base a discussion of the age problems presented by some other formation.

The Jotthian Sandstone consists of a series of light coloured sandstones, mostly reddish, often ripple-marked and current bedded, with intercalations of red and grey shale. At the base are conglomerates made up of underlying porphyries.

In the type area on the Swedish-Norwegian border near Lake Femund, the beds are comparatively flat-lying or gently folded about NNW/SSE axes, but along their western margin they are strongly upturned, locally into a vertical position. These structures are truncated by the sub-Cambrian peneplane

which is so characteristic and widespread a feature of the more eastern parts of the Fenno-Scandinavian area.

The relation of the Jottnian Sandstone to the Sparagmitian can nowhere be demonstrated by simple super position, but, due to overthrusting, must be inferred on lithological grounds and on the structure. It is important to note that the main fold lines in the Jottnian -(NW/SE)- are at right angles to the Caledonian structures.

The Sparagmitian is mostly made up of thick sandstones, markedly felspathic in the southern part, with conglomerates, and shale and carbonate horizons, the latter dolomitic in the north, of limestone in the south.

The stratigraphy of the oldest part - the 'dark Sparagmite' - is uncertain, only being seen in the zone of strong deformation and metamorphism. The succeeding dark Brottum Sparagmite and the younger 'red' or Moelv Sparagmite have a much wider present distribution and can be followed to the NW. from the Femund area to Jamtland, and into Swedish Lapland. These two Sparagmite zones are separated in the south by the Biri Conglomerate - of fluviatile origin - and, above this, the Biri Limestone - largely shaley and dark coloured, but in part massive and dolomitic. Above the red Sparagmite occurs a tillite, well developed in the northern area, in Swedish Lapland, and south of Femund.

The uppermost member of the Sparagmite formation - the

'Quartz-Sandstone' - is a transgressive formation: S.E. of Femund and in the Valdres region it overlies crystalline basement rocks, while in the central Sparagmite area it overlies a thick series of Sparagmitian sediments.

The significant features of the Sparagmitian of southern Scandinavia are that thick series of rocks below the tillite disappear in a small horizontal distance, that the tillite contains, frequently in large amount, material of great lithological similarity to the Biri limestone, stratigraphically not far below : yet angular unconformities are almost absent. Periodic uplift and erosion of the outer parts of the area of deposition must have caused the absence of beds there, while sedimentation in the central area was more or less continuous.

Further to the north and west, but still in the essentially southern part of Scandinavia, slices of highly metamorphosed Sparagmite occur in the so-called "Archaen" areas. These occurrences and the recognition of Sparagmite quartzites in the Nordfjord area north of Bergen, indicate that the sediments probably covered the whole of the southern area.

The other great area of Eocambrian rocks in Scandinavia is in the far north, in Finnmark. Here the stratigraphy is generally similar to that of the Sparagmite in the south, but there are differences in detail. The same two broad divisions exist, the older of sandstones, with a dolomite, the younger

also of sandstones, with tillite.

The most coherent stratigraphical account is that of Sven Foyn, working in the Tanafjord district (1937). His 'older sandstone series', over 3,900ft. has at the top, a zone of shales with dolomitic beds - some of the beds contain shale fragments as intraformational conglomerates. At Grasdalen are intraformational dolomite conglomerates, very reminiscent of the Porsanger dolomite (see below), the total thickness of the dolomite and shale zone being roughly 150ft. Below is the mass of the 'Older Sandstone Series' about half of the series being made up of thick, light coloured, often reddish, sandstones : about 25% is of arenaceous shale, dark coloured : and 25% is of thinner bedded alternations of the two. The dolomite and shale zone is unconformably overlain by the tillite-bearing series, although the angular discordance is very small. In general the upper series rests on successively older horizons as one goes southward ; in one area the truncation involves some 600ft. in 4 miles for example. Foyn believes that the unconformity is definitely the result of erosion and not to change in facies or the lateral thinning of beds, and described a breccia zone above the lower series, about 3ft. in thickness. The tillite above is not easily distinguished from the breccia rock, as the local rock-fragments of the breccia are dominant in the lowest part of the tillite, before less immediately derived material arrives.

The tillite bearing series has two extensive tillite zones, with 1,300ft. of brown or red sandstones, and red and green shales, between the two. Above the upper tillite are alternating light coloured sandstones and dark sandy shales, 130ft., and then 440ft. of shales, red to violet at the base, the rest blue-green.

The lower tillite has, naturally enough, a variable thickness, averaging some 200ft. It lies, as has been described, unconformably above the lower sandstone series. The rock is dominantly of silt or clay grade, a matrix in which are dispersed a variety of erratic rock fragments reaching a maximum of 6ft. in diameter, but generally less than 1 or 2ft. across. The fragments are usually entirely angular, but the edges are sometimes rounded; glacial striae have been described by Reusch (1891) and Holtedahl (1918). Dolomite most frequently occurs - not often showing any structure, but occasionally showing oolites, stromatolites, and dolomite breccia, or conglomerate ; some of these have been silicified. PreCambrian crystalline rocks are next in order of abundance, and near the southern boundary of the area in which the sediments can now be seen, they dominate. Erratics of quartz sandstone are also common.

The upper tillite is similar, and about 200ft. thick. The boulders here however are dominantly of Precambrian crystalline rocks, dolomite coming second in order of abundance : fragments of red and green shale like the shales

below the tillite are also found.

The conditions of formation of the tillites can be inferred without much doubt. Uplift, or rather slight tilting, of the older sandstone series gave a slight angular truncation of these rocks, uplift being a maximum toward the south. A thin erosion breccia was preserved by the accumulation of a thick tillite under water - for the matrix shows signs of sorting, though poor, the fragments (largely of the dolomite at the top of the 'older sandstone series') being dropped presumably by melting ice.

The continuous gradation, from the top of the tillite, into the sandstone and shale series above, indicates continuous submergence. Ripple marks occur; and it is noteworthy that a fair amount of dolomitic material is present : the shales contain authigenic pyrites grains. The sandstones show an increase in thickness from north to south; in addition the maximum grain size increases and the proportion of shale to sandstone in the series decreases. The sedimentary evidence points to a source area to the south.

The upper tillite grades from and into marine sediments and is evidently also marine. Again material from the underlying rocks supplies the 'erratic' material; the dolomite zone has presumably been much eroded and basement rocks are more characteristic.

The sandstones of the 'sandstone and shale zone' above again show frequent ripple marking. The grain size may reach

6m.m. and the grains are often angular, consisting, besides quartz, of felspar - frequently with fresh plagioclase. Sudden alternations between fissile shales and massive beds of coarse sandy material, are characteristic. The thickness of the whole series seems to vary from 65ft. to 135ft. but no areal pattern of variation is discernible.

Conditions of deposition may have become more stable in the succeeding period when over 400ft. of rather homogenous shales were laid down. One bed of sandstone, of the type described above and about 3ft. thick, occurs in the lowermost part, in the north western section of the area : to the east two additional horizons of sandstone are noted and the total thickness is somewhat greater, the evidence suggesting that the source area lay to the eastward. The possibility must be considered that these coarse sandstone beds in the general shale sequence were laid down by turbidity currents some distance from their original place of deposition. However, no mention of slumping structures or of graded bedding is made by Foyn - and ripple marked surfaces are preserved.

Above the shales just described sedimentation continues to produce sandstones and shales: the upper part of the succession being :-

	YOUNGEST:	c.640ft.- shales and fine sandstones: FOSSILIFEROUS.
		c.1280ft.- light quartzose sst.-zones of dark arenaceous shale.
5,000ft		c.1860ft.- green siltstone.
		c.640ft. - red quartzose sandstone with zones of green-grey arenaceous shale.
	OLDEST.	Shales, tillites etc. below.

The succession will not be discussed in detail, apart from a consideration of the deposition conditions. Below the fossiliferous stage - the lower sandstones, for example, are beds usually about 1ft. thick which show a bedded structure due to layers of micaceous sandstone, or clayey material. Ripple marks are common. In thin section the rock is very even grained - grain size 0.04 to 0.07mm. diameter. Quartz is the chief mineral present, with plagioclase, partly sericitised, partly fresh, and muscovite: also a few rounded grains of tourmaline and zircon.

The 1,800ft. of green or grey-green siltstones contain occasional more arenaceous beds and at the top true sandstones appear, in a gradational zone leading to the series of sandstones and shaley sandstones above. At an horizon about 1,200ft. above the base a peculiar conglomerate locally occurs - pebbles of quartz, red jasper, and yellow-green shale occur, about the size of a pea, in a groundmass of red-brown sandstone. Towards the top also, "problematical trails" are common - irregular pipes sometimes concordant

with, sometimes cutting the bedding.

The fossil bearing rocks which follow are alternating dark sandstones and dark shales, green, grey or black. The sandstone beds are rarely more than 3" thick. Fossils are commonest in the sandstones; some beds being extremely rich ("fossil breccias" - Foyn). The material has been described in detail by Strand (1935) who distinguishes the following:-

Lingulella (Lingulepsis) cf.Roberti (Matthew).
Billingsella cf.retroflexa (Matthew).
Hyolithus sp.
Trails of Cruziana type.

The Lingulella sp. is by far the commonest type found, only a few specimens of Billingsella sp. are recorded. These two brachiopod species suggest a Middle Cambrian, or possibly Upper Cambrian, age.

The fossiliferous zone is very approximately 640ft. thick and is followed by a similar thickness of light coloured quartzose sandstones.

Some 60 miles west of Tanafjord where the above sequences were elucidated lies Porsangerfjord. The Porsanger series here, isolated by thrusts and evidently allochthonous, has been correlated with the Eocambrian series of Tanafjord (Holtedahl, Foyn, etc.). A thick series of light coloured sandstones with intercalations of shaly material is overlain by a thick series of massive grey dolomites containing stromatolitic structures ('Cryptozoon') and intraformational

conglomerates. The sandstones are considered to be the equivalent of the 'older sandstone series' of Tanafjord, and above them there is a well interbedded shale-sandstone series before the dolomites begin. The similarity to the Tanafjord succession is thus close, but dolomites stratigraphically much higher than the dolomite-shale zone of Tanafjord are represented in Porsangerfjord. This agrees well with the tendency for the unconformity between the older sandstone series and the tillites above, to rise in stratigraphical horizon going N. and westward. A much greater thickness of dolomite is preserved in the Porsangerfjord district. The tillite, in addition contains fragments of dolomite with special structures common to the Porsanger dolomite - dolomite-breccia, stromatolites, ooides: actual oolites are found in the tillite but not in the Porsanger dolomite. The identification of the Porsanger dolomite with the dolomite of Tanafjord, whose stratigraphical position is known, is therefore still open to doubt, but on the present evidence it seems reasonable.

With the Sparagmite Succession augmented in northern Scandinavia by this evidence from Porsangerfjord, it may be instructive to consider another, less certainly known, area on the north coast of the Kola Peninsula to the east of Finnmark where there occurs a series of some 7,000ft. of sedimentary rocks, representing to a large extent the

Sparagmitian. On Archaen basement rocks rests a lower division of at least 5,000ft. of sandstones mainly, and with a conglomeratic base. This is followed by red and green shales, with dolomitic beds. It is claimed that stratigraphical breaks occur both below and above this latter group. Above the break lies a third division, of sandstone and dark shale. Thrust against these rocks from the north, lies another sedimentary block - largely made up of conglomeratic rocks - often with the characteristics of a tillite. The rocks of the Kola Peninsula are thus strongly reminiscent of the Tanafjord stratigraphy, but it cannot be claimed that the relationship has yet been worked out in detail.

The conditions of deposition of the Finnmark Sparagmite and the geological development of northern Scandinavia can now be discussed.

The 'older sandstone series' is entirely of shallow water origin. Conglomerates as such are very rare, but the sandstones show current bedding, and ripple marks. The shales show mud cracks and patches of clay material.

The dolomites are also shallow water deposits. Mudcracks and ripplemarks are very common in the dolomite-shale-sandstone sequence on the coast near Tanafjord for example, and intraformational conglomerates or breccias are common there and in Porsangerfjord.

The evidence points to sedimentation near land, with an

abundant supply of materials. The clastic minerals are quartz, plagioclase, mica, chlorite, microcline, zircon and tourmaline - such as one might expect from the erosion of any 'average' basement area, of gneisses and associated rock-types. The variations in thickness and relative proportions of psammitic and pelitic material indicate a source area to the south, and there such a basement complex is certainly available as a suitable postulate for the source of supply.

The unconformity above the dolomites indicates uplift to the south, Holtedahl and Foyn believing that major faulting along the line of Varanger fjord accompanied this : the evidence is inadequate. However, the block to the south was certainly uplifted and terrestial conditions existed there during the deposition of the younger series, for the material of the tillites and the interjacent shale-sandstone series was clearly derived from there. The sediments in Finnmark, however, were also exposed to erosion - so that the younger series is everywhere transgressive. The angle of the unconformity is usually low - its direction of maximum inclination - that is of the plane of truncation relative to bedding - seems to be to N.30°E or N.40°E in Tanafjord, indicating rather vaguely a tilting about a N/S or NW/SE axis.

The occurrence of the tillites as two extensive layers in a series of sandstones and shales, and the common stratification of the matrix indicates deposition in water, probably from the melting of drifting icebergs. The lower tillite

shows different types, ofteh with marked boundaries, occurring in the same area, and is presumably a compound representative of several advances of the ice mass. The thickness certainly decreases to the south, due either to a smaller deposition of material or to periods of erosion of the bottom moraine: in the extreme south however it has again increased. Evident glaciofluvial material, and some ice scouring, is locally associated with the tillites, striae running SE and NW, or E and W.

The succeeding red and brown sandstones rest on a varying substratum; in the Tanafjord district on the lower tillite; on Varanger peninsula on a coarse zone of fluvioglacial material; and even further west, around Varangerfjord, on crystalline basement rocks. The clastic minerals are fresh and little rounded, so that breaking down of the rocks by frost action may be deduced, and the period might be regarded as a cool interglacial one. Consideration of the lateral variation of these beds indicates very clearly that the sediment producing area lay to the south. Near the southern margin of the sediments coarse sandstones, often in very thick beds, predominate; further north finer sandstones occur, in less abundance, and in much thinner beds.

The upper tillite is more uniform than the lower one : unconsolidated sediments were still being eroded - fragments of clay remain but the sandstones are not present as fragments,

for they would immediately break up, unlike a coherent plastic clay. The pattern of variation of thickness of the upper tillite is difficult to interpret - decreasing from a maximum at the head of Tanafjord, towards the W. and towards the NE.

The sediments above the tillites give little evidence of facies or thickness variations, which might indicate the location of the source area. There is, however, no reason to assume that the supply area is different from that which provided the glacial material. Ripple marks indicate shallow water deposition, and the sandstones are apparently well sorted, and fine grained.

The fossiliferous beds indicate from their sedimentary petrology, and from the mode of occurrence of the fossils, that they were laid down comparatively rapidly.

Before turning to the development of the Cambrian system, a few remarks on the Sparagmite formation of the far south, at Lake Mjosen, will be made to complete the synopsis.

Goldschmidt (1908) and Kiaer (1916) in particular have contributed to the knowledge of this district - but Th.Vogt (1924) has synthesized the previous work with his own observations and produced a coherent history.

The lower part of the Sparagmite series here consists ofnearly 1,000ft. of dark grey, generally coarse sandstones, rich in felspar grains, with some layers of dark arenaceous shale. Then follows a relatively thin zone with red and

green shale, and thin beds of limestone. Holtedahl (1922) considers that the thick lower sandstones tell of rapid sedimentation of material derived from granites and gneisses of the basement : conditions changed to give slow deposition in the succeeding period. Rejuvenation must then have occurred, for the very coarse conglomerate - the Biri conglomerate - follows, between four and six hundred feet thick in places, and with boulders reaching 3ft. in maximum dimension. The boulders areof granite, gneiss, quartzite, limestone, and 'diabase', and are well worn, and distinctly rounded. Transport, in water, of such coarse material clearly indicates high relief. An intermediate zone of grey felspathic sandstone and shale follows and then the Biri limestone - the thickness of which reaches three or four hundred feet. The limestone is compact and grey, usually with some magnesian content, often arenaceous: characteristic however, is a black argillaceous limestone facies. At Lake Mjosen in the compact variety are intraformational conglomerates - and oolites and stromatolitic limestones - all indicative of shallow water deposition. The limestones are followed by the younger 'red sparagmite' - a pink (felspathic), coarse, often conglomeratic, thick bedded sandstone, over 1,200ft. thick. The conditions of formation of this 'sparagmite' (or felspathic sandstone) and rocks of similar facies of the same general Eocambrian age has been discussed by Walther (1909), and by several Norwegian geologists, notably Holtedahl (1922) and (1920).

They have concluded that the sediments have been produced by the weathering of granitic rock in a very dry climate: but the grains are coarse and angular and obviously not of a wind blown desert sand deposit. Transport was evidently short and rapid, in torrential waters, derived from a mountainous borderland in semi-arid conditions. The term red sparaqmites should not evoke a comparison with the red sandstone facies of, say, the New Red Sandstone, for there the colour is not due to the presence of felspar. The 'Sparaqmite' deposits indicate much more rapid accumulation than ordinary 'red sandstones'.

The red sparaqmite has frequent conglomerate zones, with well rounded, water-worn boulders of moderate size: but this passes up into a rather more peculiar conglomerate (the Moelv conglomerate) which Holtedahl considers is definitely a tillite. It has a red-brown colour, with no visible bedding, but consists of fragments of all sizes embedded in a fine-grained matrix. The smaller fragments are angular, and the larger, which reach nearly 2ft. in diameter, are only partially rounded. The fragments consist of granite, gneisses, sandstones and quartzites, and limestones - particularly at Lake Mjosen where they are lithologically like the Biri limestone - and, in an area east of this near the Swedish frontier north of Trysil, there occur porphyries of types corresponding to parts of the Precambrian exposed even farther to the east. This tillite, Holtedahl points out,

is exactly like the brown tillites of Finnmarken (Holtedahl, 1919) - and in common with them must have been deposited in water - as the result of melting ice bergs, or, more consistent with its character here, as morainic material in front of a partly submerged ice mass.

The tillite - 40ft. or more thick at Lake Mjosen is followed by a thin zone of red and green shale, and some sandstone beds (150ft). Above these lies the "Quartz Sandstone" - a normal sandstone consisting of quartz grains, finer, rounder, and more evenly sized (.45 to .55mm) than those of the true 'sparagmites' : but even here intercalations of sparagmite facies occur, and the bottom part of the lower of the two divisions of the 'Quartz Sandstone' - namely the Vardal Sparagmite - is coarse-grained and felspathic in part. This Vardal sparagmite shows current bedding, and some lateral variation : in general one may say that towards the east of the Lake Mjosen area the grains are well rounded and have a clayey matrix (in very small amount) - the minerals present being quartz, microcline, plagioclase. Toward the west they are more variable in size, and more angular.

A transition zone in which the felspar content of the sandstone steadily decreases, introduces the upper part of the Quartz Sandstone, - the Ringsaker quartzite. The minerals are mainly quartz - of the same grain size (about 0.5mm.) as the Vardal Sparagmite - and the heavy minerals

tourmaline, zircon, and rutile.

The significance of this division of the Quartz Sandstone into two parts, the lower felspar bearing, the upper purely quartzitic, has been discussed by Vogt (1924). He points out that the general character of the Sparagmite formation (sensu lato) of Scandinavia indicates deposition as a result of rapid uplifts of the borderland. The Quartz Sandstone is a particularly good example from several in the whole formation, which tells of denudation reducing relief in the borderland so that transport gradually becomes less violent and rapid; chemical activity is more prolonged, and pure quartz sandstones, lacking in felspar, are formed. The stable residual heavy minerals are significant in this respect. Vogt regards the Ringsaker quartzite as marking the end of the periodic epeirogenic movements, characterising the Sparagmitian, and introducing the calm period of the Lower Cambrian.

Vogt criticises the view that the Sparagmites were formed in an arid climate. He admits the existence of widespread desert conditions - but points out that these would develop during that part of the history of the earth prior to the large scale migration of plant life onto land, without relation to the amount of precipitation. There is in addition much evidence of strong chemical activity, and the presence of felspar in the sandstones is to be interpreted as indicative only of rapid transport. (cf.Walther,1909).

As to the direction of derivation, Vogt agrees with

Holtedahl that land lay to the south west : the evidence is, however, in the present writer's opinion quite inconclusive -. It is based on the view that a small amount of compact quartzite detritus is derived from the Telemark quartzite - now found to the south west of these Sparagmites : and the fact that the sand grains are angular to the west and well rounded in the east.

The area over which the Quartz sandstone was deposited, was markedly larger in the south of Scandinavia, than the areas of the earlier felspar-bearing sandstone zones.

The Cambro-Silurian Series of Scandinavia.

The history of the Lower Palaeozoic sediments of Scandinavia, is much more precisely known than that of the Eocambrian, for with the help of the palaeontological evidence the structural uncertainties can be overcome. The account will therefore be rather more straightforward, as it is unnecessary to discuss tentative correlations and possible relationships here.

A fairly complete, non-metamorphosed succession is only found in parts of the Jamtland district of Sweden, and in the Oslo area. Elsewhere the stratigraphical knowledge is fragmentary, tied into the main scheme by the presence of (often poorly preserved) fossils, or on lithological grounds.

Over large areas in Scandinavia the Lower Cambrian was a period of transgression. The Sparagmite areas of the south lay at a relatively low level, and were later covered, by pelitic material. The adjacent areas to east, south and west remained above sea level, or were just flooded - conglomerates occurring above the peneplaned surface of 'basement complex'. Towards the end of Lower Cambrian times the sea had reached the central Raudsfjord district, and Finse. In Jamtland there is evidence of Cambrian transgression from west to east; and further north the Lower Cambrian shore line ran NNE-ward from the Mjosen district into northern Sweden - the sub Cambrian surface dipping to the NW. In this northern part - along the "Glint" - the Lower Cambrian is represented by what is known as the "Hyolithus zone", made up of multi-coloured shales, and sandstones.

Middle Cambrian times began with further transgressions - black alum shales of the Middle and Upper Cambrian were deposited over very large areas in the south, and probably the northern districts, where alum shales rest on the Hyolithus zone.

The Ordovician of the Oslo and eastern Jamtland districts consists of alternating limestones and shales (often of typical graptolitic shale facies). To the east the percentage of terrigenous material decreases, while further west the shale-to-limestone ratio increases, and the total

thickness becomes greater. Thus in Gausdal, north west of Mjosen, the Arenig Megalaspis limestone of Oslo is replaced by arenaceous slates - with graptolites. In Jamtland the development of the "Follinge-Holmsjo" facies represents shales and sandstones - the material of which according to Holtedahl (1938) is largely derived from the Olden granite (PreCambrian) to the north west.

All the sedimentary petrology thus gives evidence of a land area to the west or north west of the general 'central Sparagmite area' between the Jotunheimen and Jamtland.

In the coastal regions, around Trondheim, a different facies is met with. The Sparagmite formation is represented here, and the Cambrian presumably is missing, for the lowest series of rocks with fossils are those of the Roros Group - mica schists, with quartzites, limestones, and amphibolites or 'green stones'. Dictyonema flabelliforme dates part, at least, of the group, as basal Ordovician (in the American sense). The Bymark group follows - greenstones, in places pillow lavas, and quartzites, beds of red jasper chert, and limestone. Above these lies a greenstone-conglomerate containing pebbles of the Bymark rocks, and intrusions, probably of the same age- gabbros and trondhjemite. Important earth movements had thus occurred before the deposition of this conglomerate, and are presumably the representatives of the Taconic phase of the Caledonian (s.l.) orogeny - directly

equivalent in age to the post-Tremadoc earth movements of North Wales and other districts.

Above the conglomerate lies the Hovin Group - beginning with a thick series of shales and slates, the lower parts of which have yielded species of Trinucleus and other fossils indicating a Llandeilian (or even earlier) age. Higher, graptolites such as Dicranograptus, etc., indicate Caradocian rocks. The slates are overlain by the Hovin sandstone, with a poorly preserved fauna of brachiopods and gastropods indicating, somewhat dubiously, a Caradocian age. Farther to the north west and west, it seems that the Hovin sandstone gives place to the Holand Series, with limestones containing corals, etc., this change being analogous to NW/SE directional changes of facies in Scotland - from limestone to graptolitic shale.

On the island of Smola off the coast west of Trondhjem occurs limestone, in association with a quartz-conglomerate and a series of lavas referred to the Bymark Group. The limestone has a fauna of silicified gasteropods indicating a Canadian age - and the assemblage is 'of American type' - having a distinct resemblance to the fossils of the Durness limestone and the Bear Island Upper Dolomite Series - both of Canadian age, and to similar faunas in N.America (Newfoundland) and East Greenland. These facts are discussed more fully later (p. 249).

Other areas of Ordovician rocks on the west coast, around Bergen, are generally related to the facies developed at Trondhjem, but some differences of opinion on the succession remain. The greenstone series of this district may perhaps be younger than the Lower Ordovician. Fossils, including corals, higher up fix part of the succession as uppermost Ordovician. The coral species are largely identical with those from the Oslo region. Volcanic and sedimentary rocks, like those of Trondhjem also occur in the eastern parts of northern Scandinavia.

To the west, however, including the large district of Nordland, mica schists and thick massive limestones and dolomites are characteristic, but volcanites, and conglomerates and quartzites do occur. Fossils are few - and indicate Middle or Lower Ordovician age for part of the succession. The series is of very great thickness, and parts of it may be pre-Ordovician.

The Silurian rocks of Scandinavia are best known from Oslo, where the basal zone, of conglomerate and sandstone, indicates slight uplift, and the erosion of Ordovician limestones. Further north this zone seems to consist of sandstone only. Above is an alteration of richly fossiliferous limestones, and shales and finally Downtonian sandstones with eurypterids and fish.

In Bergen, and the north east Trondhjem districts the rocks identified as Silurian represent only the earlier part of the period: a Rastrites fauna has been found in a series of altered conglomerates, sandstones and shales, called in the Trondhjem district, the Ekne Group.

In Jamtland, the non-metamorphic Silurian is made up mainly of shaley and sandy material, with a Pentamerus limestone. In northern Sweden, around Bjorkvattnet, occur a series of slates, quartzites, limestones, and a conglomerate which is probably basal Silurian. Fossils above indicate 'Llandovery' age. Some authors believe that a series of volcanic rocks in this district are of Silurian age - but the matter is strongly disputed.

The main period of orogeny and metamorphism of the Caledonian was later than all these sediments. At Oslo the Downtonian sandstones are affected by the earth movements, but in the outer parts of the Trondhjem district there occurs a metamorphosed series of conglomerates and sandstones, in which is found Dictyocaris. These Downtonian deposits rest with angular unconformity on altered Cambro-Silurian sediments and associated intrusions. It is thus possible to say that while the main phase was pre-Downtonian in the Trondhjem area, it was post-Downtonian further to the SE in the Oslo region.

GREAT BRITAIN.

There seems to be room, in the present state of knowledge, for a wide variety of views on the Caledonides of Gt.Britain, and particularly on the early part of their history. The picture presented in this Thesis is one of these views: the difficulties and uncertainties are well known, so that that there is no need here to mention every alternative and argument.

The oldest rocks which are essentially part of the Caledonides of Britain are the Moine Series. They now lie, thrust in a north-west-ward direction, over a comparatively little folded and metamorphosed mass of rocks forming the N.W. coastal strip of the Highlands. This strip has acted, apparently as a stable or rigid unit, showing no signs of marked foreshortening in the evolution of the Caledonian (s.l) fold belt. Crystalline Lewisian rocks are overlain unconformably by typical post-orogenic sediments of the Torridonian. Unconformably above these lie the sediments of the transgressing Lower Cambrian Sea. The age of the Lewisian and Torridonian is not very important here. It seems reasonable to consider the Lewisian, with its NW/SE structural grain, and Pre-Torridonian metamorphism, as something essentially earlier than the beginning of the Caledonian cycle. The Torridonian may be equivalent to

the Moines : it would seem difficult to justify this by a correlation of their lithology, but some would argue that anomalies are due to facies changes. Yet in the absence of fossils, and lacking decisive evidence from igneous activity, it seems that the only possibility of proving their identity directly must be based on lithological grounds. As has been mentioned before (p.189) the Jottnian of Scandinavia is a deposit resembling the Torridonian, but it can be dated as pre-Sparagmitian on structural grounds more easily than the Torridonian can be shown to be older than the Moines. Despite this, the present writer's opinion is that the Torridonian is essentially a post-orogenic formation related to the last Lewisian orogeny, and not truly part of the early Caledonian rocks.

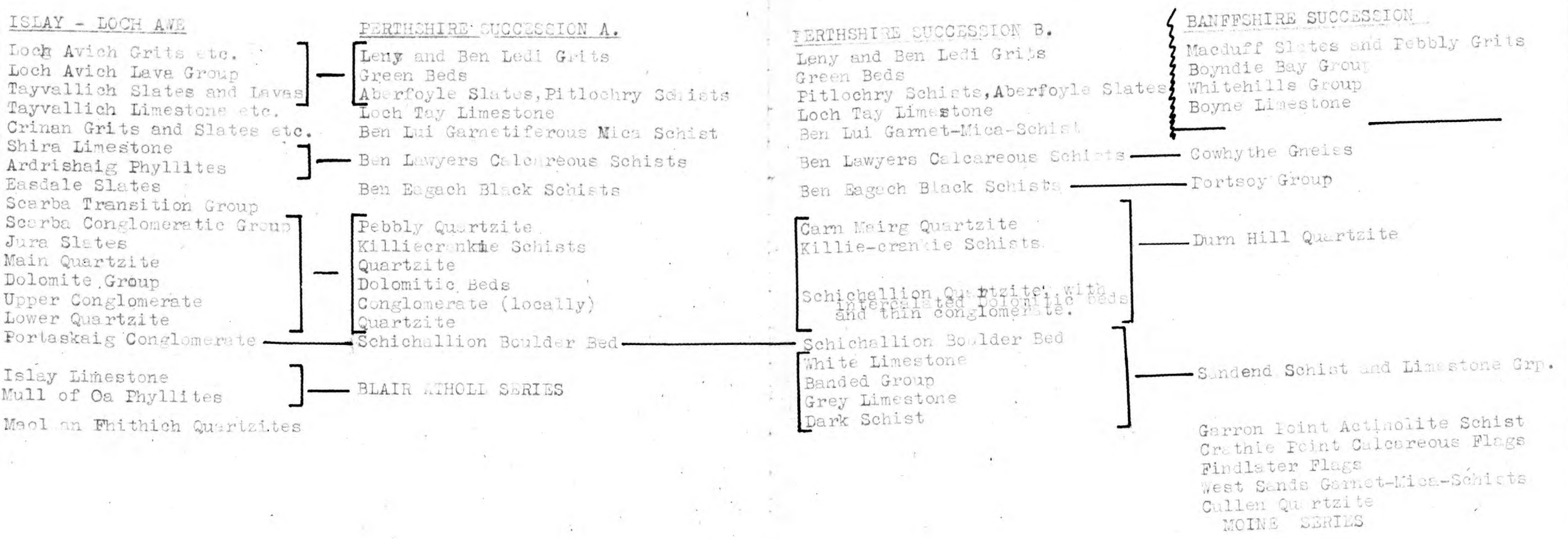
The Moine, Dalradian and early Cambrian sediments, then, were deposited in a belt running roughly from the NW coastal strip to the Midland Valley of Scotland. In the central area the sedimentation was, broadly speaking, continuous - the Dalradian following the Moine Series, and continuing up into the Cambrian. The Cambrian marks the point at which subsidence of the NW borderland led to marine transgression over the Lewisian and Torridonian rocks. The stratigraphy of this immense thickness of sediments will be described briefly, with a view to understanding the conditions of deposition, and comparing it with the development of other areas.

The Moine Series is poorly known stratigraphically. Essentially it consists of a monotonous assemblage of fairly uniform rock types, in the semipelitic category. Beds of pure quartzite, pure pelitic rocks, and pure limestones, are rare. Conglomerates have been 'recognised', but they are always dubious in appearance and tend to become 'autoclastic melanges' when examined critically. Banded series of hornblende granulites, alternating with semipelitic rocks have been regarded as metamorphosed calcareous rocks, and as former basic volcanic ashes by different authors. Local successions have been worked out but attempts at widespread correlation have so far failed. The inherent character of the original sediments, that is their poor differentiation, must inevitably make correlation difficult, apart from the immense complications of the structure.

Ritchey and Kennedy (1939) formulated a succession for 19,000ft. of sediments in the Morar districts, which they were able to follow over a good part of the southern 'Moine' area, even into Mull :-

Upper Psammitic Series		12,000ft.
Pelitic Series	(Upper striped schists)	
	(Pelitic schists)	3,000ft.
	(Lower Striped schists)	
Lower Psammitic Series		3,500ft.

Diagram 29.


ISLAY - LOCH AWE
Loch Avich Grits etc.
Loch Avich Lava Group
Tayvallich Slates and Lavas
Tayvallich Limestone etc.
Crinan Grits and Slates etc.
Shira Limestone
Ardrishaig Phyllites
Easdale Slates
Scarba Transition Group
Scarba Conglomeratic Group
Jura Slates
Main Quartzite
Dolomite Group
Upper Conglomerate
Lower Quartzite
Portaskaig Conglomerate
Islay Limestone
Mull of Oa Phyllites
Maol an Fhithich Quartzites
BLAIR ATHOLL SERIES
PERTHSHIRE SUCCESSION A.
Leny and Ben Ledi Grits
Green Beds
Aberfoyle Slates, Pitlochry Schists
Loch Tay Limestone
Ben Lui Garnetiferous Mica Schist
Ben Lawyers Calcareous Schists
Ben Eagach Black Schists
Pebbly Quartzite
Killiecrankie Schists
Quartzite
Dolomitic Beds
Conglomerate (locally)
Quartzite
Schichallion Boulder Bed
PERTHSHIRE SUCCESSION B.
Leny and Ben Ledi Grits
Green Beds
Pitlochry Schists, Aberfoyle Slates
Loch Tay Limestone
Ben Lui Garnet-Mica-Schist
Ben Lawyers Calcareous Schists
Ben Eagach Black Schists
Carn Mairg Quartzite
Killie-crankie Schists
Schichallion Quartzite with intercalated dolomitic beds and thin conglomerate.
Schichallion Boulder Bed
White Limestone
Banded Group
Grey Limestone
Dark Schist
BANFFSHIRE SUCCESSION
Macduff Slates and Pebbly Grits
Boyndie Bay Group
Whitehills Group
Boyne Limestone
Cowhythe Gneiss
Portsoy Group
Durn Hill Quartzite
Sandend Schist and Limestone Grp.
Garron Point Actinolite Schist
Crathie Point Calcareous Flags
Findlater Flags
West Sands Garnet-Mica-Schists
Cullen Quartzite
MOINE SERIES

This work was facilitated by the preservation of original sedimentation structures in this area : in other parts of the Moine area, where these are lost the problem becomes more difficult. More local successions have been arrived at, but no other large scale estimate of the total thickness has been attempted, except for the Fannich Forest area - "4,000ft. plus several thousand feet."

The Moine/Dalradian junction shows a variety of relationships, often tectonic, but there is evidence that the very siliceous upper part of the Moine is followed conformably by the basal quartzites of the Dalradian. Thus, in the NE, the Cullen quartzites pass down into the Moine; in the Central Highlands the Ben Aigan quartzite, has the same relation: in Donegal J.G.C. Anderson has arrived at the conclusion that the Moines run conformably up into the Dalradian.

The stratigraphy is still debatable, but knowledge has now reached a point with the use of techniques for determining order of super-position from sedimentary structures, from which it seems possible that detailed work will eventually reach conclusions that can be generally accepted.

The Perthshire Dalradian Succession is perhaps the most complete in the SW part, and is detailed in the diagram (No.29) column 2 , in a synthesized form,

Various further partial successions have been put

forward for areas in the SW., but these will not be dealt with in detail. However the work in Islay, Jura, Scarba and the Loch Awe region, has produced a fairly coherent succession, which can be correlated to the Perthshire succession, as shown in columns 1 and 2 of the diagram.

The standard succession in the NE. is that of the Banffshire coast, which is shown with the postulated correlation of the lower division of the Banffshire succession (the Keith Division) to the Perthshire succession. The upper division, above the Boyne Line - in the Banff Division - seems not to be equivalent to any part of the Perthshire succession. The Green Beds of Perthshire, for example, are absent and a previous attempt by Horne to correlate the Macduff Slates with the Aberfoyle Slates, and the Boyne Limestone with the Loch Tay Limestone was disposed of when one succession was shown on sedimentation evidence to be right way up, and the other in reverse order.

In the Highland Border, J.G.C. Anderson (1947) has claimed to show the following sequence; the Dalradian transition to the Lower Palaeozoics :-

DOWNTONIAN

	Post-Arenig Group	?Caradoc	:Breccias, conglomerates, grits, limestones.
	Arenig		:Spilites, black shales, cherts.
?disconformity?			
Upper Psammitic Group.	(Upper Grits.		:grits with pelitic bands.
	(Leny Limestone and Shales		:limestone & black shales.
	(Lower Grits		:grits with pelitic bands.
	(Epidotic grits.		
	Upper Pelitic and Calcareous Group.		:slates, phyllites & mica schists with psammitic and limestone bands.

The relationship to the Perthshire rocks is as follows:- The Upper Pelitic and Calcareous Group are the equivalent of the Aberfoyle Slates. The Green Beds, and Epidotic Grits, are locally developed; they may be equivalent. The Lower Grits are the Leny or Beni Ledi Grits of Perthshire. The Leny Limestone is equivalent in the Callender and Glen Fruin occurrences. The Upper Grits are equivalent to the Rothesay Grits of Bute, in part, and the North Sannox Grits of Arran.

It is important to note that these divisions were mapped as Dalradian in the first place, and the correlations above were made before the Middle Cambrian age of the Leny Limestone was suggested. The correlation of these rocks

with the upper part of the Dalradian was made without any ulterior motive.

Pringle (1939) dated the Leny Limestone on the evidence of trilobites and thus showed that the metamorphism and folding of the Dalradian could not be Pre Cambrian in age. Details of the fauna have not yet been described, unfortunately, but dominant in the collection is a new species of Pagetia - a form typical of the American Middle Cambrian.

Having reached fossiliferous rocks, problems of correlation become simpler. We may now turn to Cambrian rocks elsewhere.

The northern borderland sank at the beginning of the Cambrian. In the NW the rocks are preserved beneath the Moine Thrust zone.

The details of the lithology are well known. What is important is the dating of various horizons. The first datable fossiliferous zone occurs near the middle of the Fucoidl Beds, where a fauna very similar to that of the Olenellus zone of N.America occurs with Olenellus lapworthi, Olenellus reticulatus, Olenelloides armatus; and Hyolithes and Salterella. Olenellus is also found in the Serpulite Grit. In the lowest 30ft. of the Grudaidh Group of the Durness Limestone, and less certainly at an horizon in the Eilean Dubh Group, Salterella has been recorded, and on this basis the beds have been taken as the Lower Cambrian. In the Saillmhor group above, a few gasteropods and cephalopods

have been found, and an 'asaphoid' trilobite. The assemblage is not absolutely diagnostic, but suggests an Ordovician age (the Tremadoc, Canadian, Beekmantown groups, etc., are taken as belonging to the Ordovician). The Sangomore Group is unfossiliferous, but the Balnakiel and Croisaphuill Groups above are richly fossiliferous, and the fauna, mostly gasteropods, and cephalopods, is listed ~~overleaf~~ below :-

Maclurea acuminata.
Hormotoma (Murchisonia) antiqua.
" dubia
Lecanospira (Ophileta) compacta.
Trochonema? (Oriostoma) calphurnia.
Enconia thule.
Helicotoma spinosa.
Protocycloceras (Actinoceras) mendax.
Piloceras invaginatum.
Endoceras spp.
Euchasma blumenbachi.
Petiguras (Bathyuras) nero.
Archaeoscyphia ep.

The assemblage is almost identical with that of the Beekmantown Limestone of North America, and its age is quite definitely Lower Ordovician - Canadian. A comparison of Canadian faunas in the various districts is undertaken later (p. 249).

We have, then, a series of rocks with Lower Cambrian Olenellidan fauna, separated from a series with lowermost Ordovician faunas by about 300 to 400ft. of unfossiliferous dolomites. The Upper and Middle Cambrian must be represented either by a stratigraphical break or breaks, or a condensed sequence of extremely small thickness. Grabau regarded a thin breccia in the Eilean Dubh group as significant,

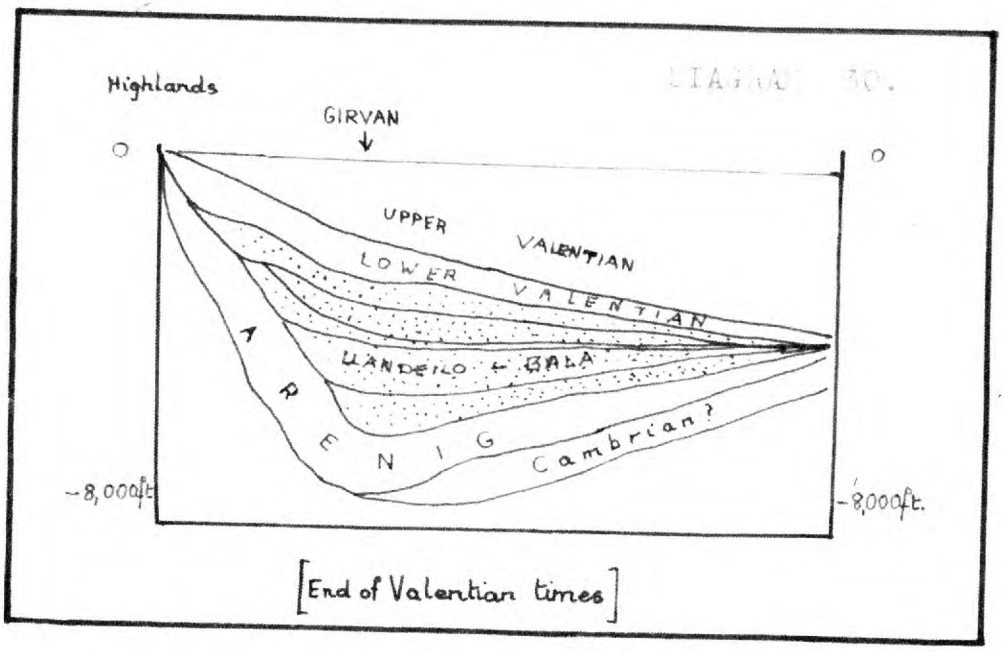
probably indicating a disconformity; but Peach and Horne disagreed. The question is clearly debatable; but no one will deny that the sediments of the Middle and Upper Cambrian are either extremely thin or missing : and that no Middle or Upper Cambrian fauna is preserved. The importance of this is emphasized later (p.252).

The succession in the Highland Border area has already been described. Further to the south, Cambrian transgression onto the crystalline basement occurred over wide areas. The detailed stratigraphy is not important in this connection, but the rock types and their inferred mode of formation are of interest. The Welsh facies are well known and the modern work tends towards confirming the view that the area was in part under 'deeper' water. The graded beds of the Cambrian grits alternating with shales contrast markedly with the much thinner well washed quartzites of Shropshire, Nuneaton and the Malverns, with their occasional limestones. The downward movement of the floor of the basin of sedimentation can be compared fairly accurately in the various localities and is very different from place to place. Certainly the deposits in the thicker successions indicate more rapid deposition; and more abundant supply of detritus. The early part of the period is everywhere represented by coarse material deposited in shallow water: pebble beds and coarse grits. In Middle and Upper Cambrian

times deeper water sediments occur, and by Tremadocian times deposition of dark shales was general.

The fauna of the Cambrian rocks in the south is strikingly different from that of the Durness succession. The evidence points strongly in favour of supposing a land ridge to have separated the two areas of deposition, the northern and the southern. Within the southern region, the distribution of facies is somewhat irregular, and does not indicate a greatly elongated trough, but rather a series of cuvettes, with deeper water, and greater thickness of sediment, in their centres. For various areas of the Cambrian of Wales the sediments have been said to be derived from the west, north-west, north, east, south-east, and south; and the plotting of thicknesses indicates a maximum, of probably 16,000ft., in the Harlech Dome region, falling quite rapidly to north, east and south.

The Ordovician rocks indicate a similar distribution of sedimentation into somewhat restricted areas - the point of maximum downwarping shifting from one period to the next, the main source area changing quickly, as negative areas became positive, and local rejuvenation occurred. From these facts, and even more strongly from the Silurian rocks, we obtain a picture of conditions which were extremely erratic, and - in the present writer's opinion at least - not of great significance in comparison with the major downwarp to the north. The Southern Uplands 'geosyncline'



[End of Valentian times]

and the 'Welsh Geosyncline' were comparatively conspicuous features, but they seem to have been bucklings developed at a late stage in the history of the Caledonides and are (consequently?) but little affected by the Caledonian orogeny.

Let us return to the southern boundary of the Highlands. Here during Ordovician times a large thickness of coarse greywackes (4,400ft) were deposited whilst some 290ft. of graptolitic shales were formed at a point out of reach of the coarse detritus. The section (diagram 30) is by now classic.

The 'second cycle' sediments - greywackes and so on - in their immense thickness, rapid deposition, lack of sorting, and their distribution, suggest the north Scottish area of deposition had begun its career as a positive area; and that the metamorphism and the main folding of the sediments north of Girvan began in Middle Ordovician times, much earlier than the folding which affected the English and Welsh areas.

S U M M A R Y.

We have considered at some length the detailed stratigraphy of the Caledonides of Svallard, Scandinavia, and Gt. Britain. The question now arises: do the sediments indicate similarities in the broad development of conditions in these widely separated areas? The upper parts of the successions we can correlate and compare unhesitatingly, on palaeontological evidence. The presence of Eocambrian tillites of similar character in all the successions, suggests that the glaciation they record may also be used as a time marker, in the absence of fossils.

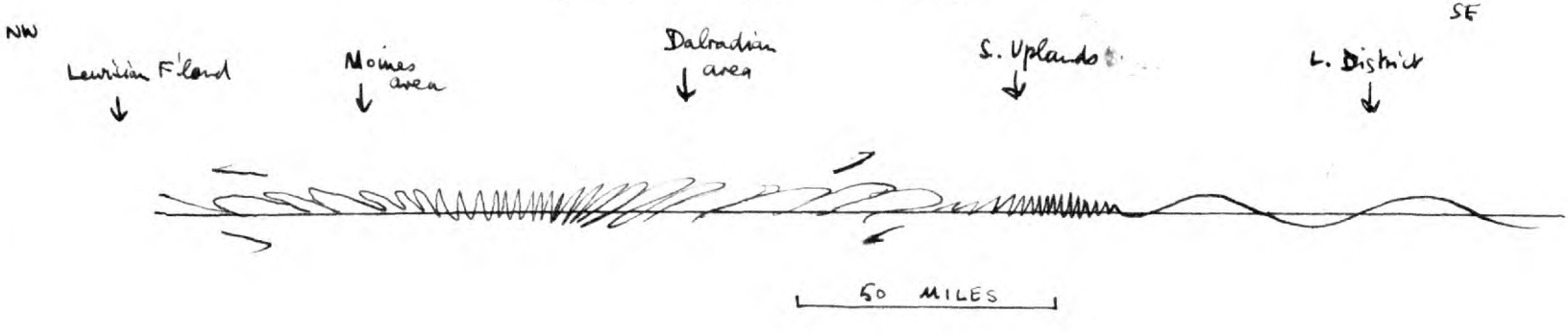
We may generalise thus : in each area, crystalline PreCambrian rocks are overlain by an immensely thick series of sediments which represent a major cycle of sedimentation. The earlier deposits are poorly differentiated, rapidly formed, and contain a great proportion of land-derived material: these are the lower parts of the Murchison Bay formation in Spitsbergen, the Older Sparagmite of Scandinavia, and the Moine Series of Scotland. In the later part of the series the sediments are more slowly accumulated, show better differentiation into purer, less mixed, lithological types, with a rising preponderance of carbonates; - the upper Murchison Bay formation, the Younger Sparagmite and the lower part of the Dalradian Series.

At this point general glaciation occurred, with local

upwarping and erosion of beds just laid down. Glacial deposits were formed in water, in very close association with the deposition of dolomitic limestones in shallow water. These tillites are the Sveanor formation in Spitsbergen, the Moelv-Finnmarken tillites of Norway, and the Portaskaig-Schihallion boulder beds of Scotland. Above the glacial deposits occur further series of sediments reaching into Cambrian times, where the first fossils are recorded - the Cape Sparre formation, Spitsbergen; the Tanafjord Series, Norway, and possibly the Dalradian in Gt.Britain.

No further evidence can be adduced of events in Spitsbergen, but in Scandinavia and Britain there was widespread extension of the areas of deposition at the beginning of the Cambrian, and a series of oval downwarped areas developed to the south-east, rather different in their erratic form and shifting position from the very long trough in which the Eocambrian sediments had been steadily accumulated. The earlier Cambrian - at Tanafjord and Durness - is characterised by the abundance of land derived material, the supply of which gradually diminished in relation to the proportion of carbonates. In 'Canadian' times dolomitic limestones were being deposited in shallow water, a distinctive assemblage of gasteropods, cephalopods, sponges and corals being preserved; - the Younger Dolomite Series of "Bear Island, the Smola limestones, the Balnakiel and Croisaphuill groups of the Durness succession. In Bear Island these conditions

DIAGRAM 31.


NW
SE
Laurician F'land
Moines area
Dalradian area
S. Uplands
L. District
50 MILES

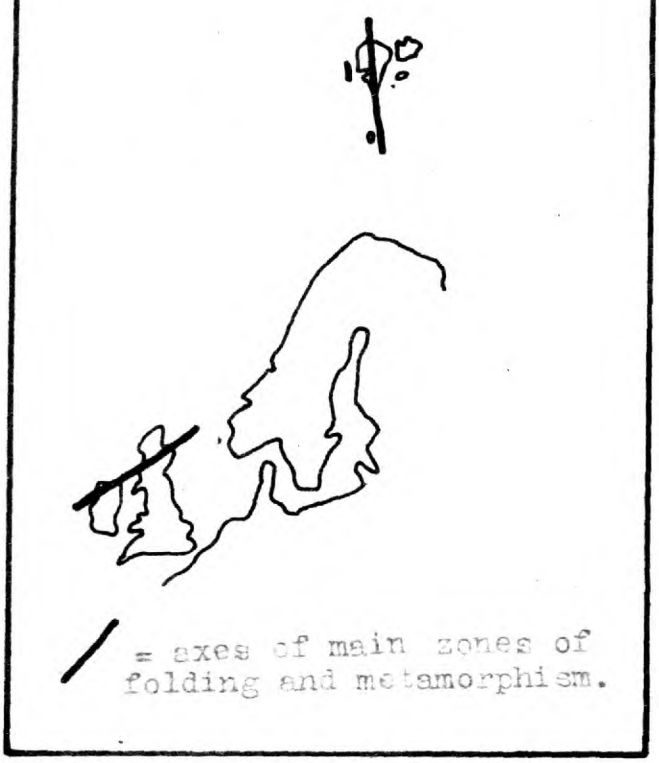
continued to 'Black River' times.

Not much later, the main phase of folding and metamorphism began; this supplied fresh material for the troughs to the south-east (Southern Uplands and S.Norway) where second cycle sediments accumulated. The folding spread south-eastwards as time went on. Final major uplift, after folding had eased, began in Downtonian times in the north-west: further south at the end of the Downtonian. Extensive and thick post-orogenic sediments accumulated in the Devonian period - in Spitsbergen, S.Norway and in Britain.

Is there a corresponding unity of structure? The diagrammatic section (diagram 31) is an attempt at a generalisation of Caledonian structures in Britain. In the N.W. Highlands, folding in the Moine Series is directed towards the west, south-west or north-west, that is toward the rigid foreland now exposed to the west. The Dalradian rocks, in the southern part of the Highlands, are overfolded in the opposite direction, so that the master structure is symmetrical with two belts of folding directed outwards from a central line. To the south of this symmetrical zone of intense deformation regional metamorphism is absent and the folding is more gentle - isoclinal structures in the Southern Uplands giving way to the open anticlines and synclines of the Lake District and Wales.

The section shows a remarkable resemblance to that

DIAGRAM 32.



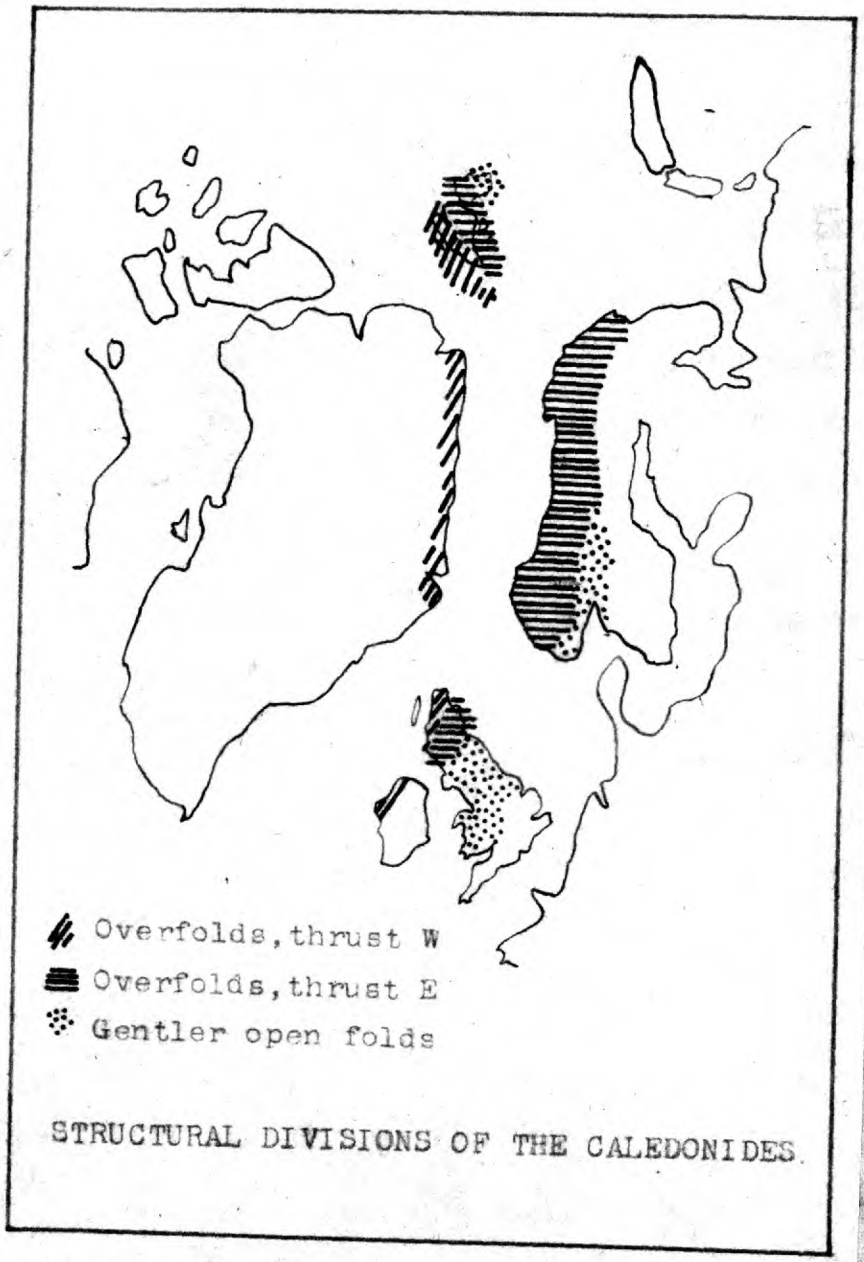
/ = axes of main zones of folding and metamorphism.

drawn for Spitsbergen (diagram 24, p.146) the width of the zone of intense deformation and regional metamorphism is about the same in each case - 150 to 200 miles. There are many further similarities, for example in the patterns of metamorphism and migmatisation, the distribution of late-stage cross-cutting plutons, and the post-orogenic block faulting, which controlled Devonian sedimentation.

In Spitsbergen, and in Britain, then, the Caledonian orogen is made up of a belt of metamorphic rocks which has a symmetrical structure with overfolding on each side directed outward from a "central zone": to the east or south-east, gentler open folding indicates less intense foreshortening, and there has been no real regional metamorphism.

The disposition of these "central zones" - the lines of symmetry running through the middle of the belts of intense deformation - has been plotted on diagram . Clearly we should examine the structure of Scandinavia, expecting to find a similar disposition and symmetry. The area of gentler structures to the south-east is present (in south Norway) but in the main belt, only overfolding and thrusting to the south-east is developed.

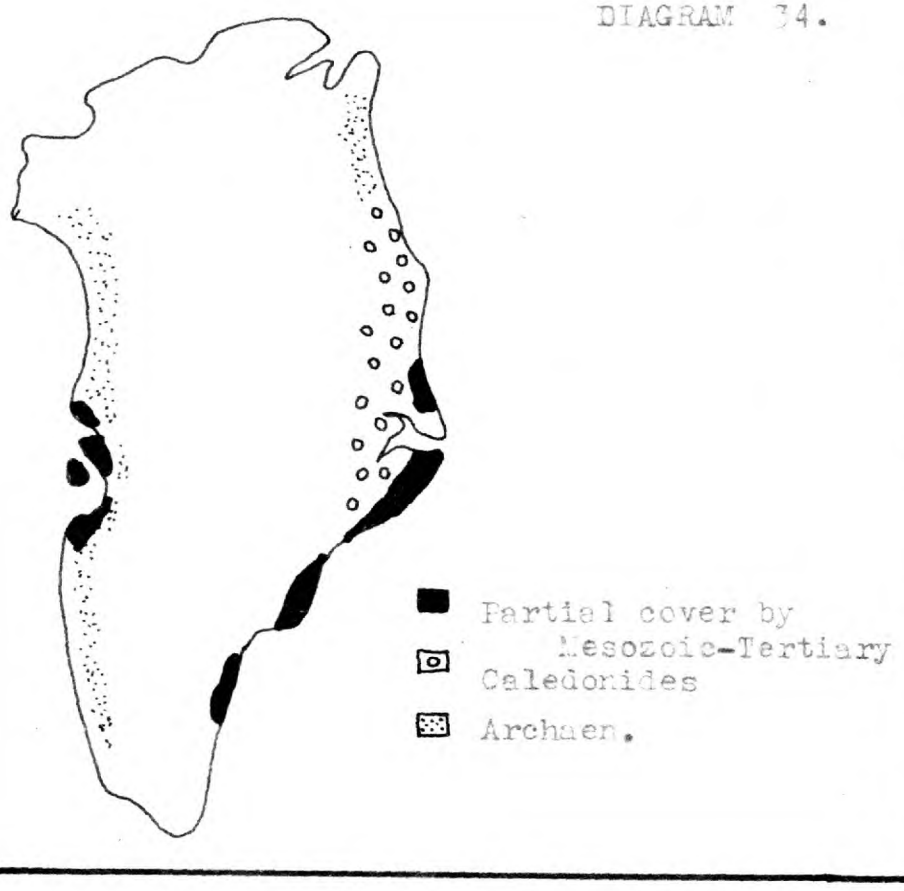
In diagram 32 , the distribution of belts of westward folding and eastward folding are indicated, and also the areas of gentler open structures. For Norway we must postulate either that the 'westward belt' once existed, to the west of



STRUCTURAL DIVISIONS OF THE CALEDONIDES.

the present coastline, or that the symmetry of the Spitsbergen and Scottish Caledonides never extended to Scandinavia, where compression might have resulted in all folds moving in one direction. However it seems a little unlikely that the folding in Scandinavia should take this form, while the structure in Scotland and Spitsbergen gives no hint of such a pattern. The more likely alternative is that a belt of westward overfolding lay to the west of Norway. It may be suggested that it is now submerged, downfaulted, off the Norwegian coast. But the presence of a Caledonian fold belt of the correct dimensions, the correct disposition, and the correct structure, along the east coast of Greenland, suggests a working hypothesis for the final part of this review of the Caledonides of the North Atlantic-Arctic province. The present-day distribution of the Caledonides of the province is best shown on an oblique cylindrical projection - diagram 27, p.181. If we manipulate the two sides of the Atlantic Ocean so as to bring the fold belt of Greenland into the position of the missing belt west of Norway, we achieve a structural unity - diagram ~~27 p.181~~ 3:3. This may, of course, be pure coincidence; but if we can discover evidence from the rocks of Greenland that they once formed part of the same geosyncline as that from which the Spitsbergen-Norwegian-British Caledonian fold mountains were built, then we shall have gone some way toward showing that the geology of the North Atlantic makes more sense if Continental Drift is possible. We will, then, examine the Caledonides of Greenland.

DIAGRAM 34.



G R E E N L A N D.

The general geology of Greenland is summarised in the diagram 34 opposite.

The Archaean gneisses, which form the basement complex over which the Caledonides have developed, show at least two PreCambrian orogenic cycles, and in the Umanak area on the west coast, a third. In the north beyond Thule, a series of Cambro-Ordovician rocks (and in the far north Silurian) rest unconformably upon the late PreCambrian "Thule formation" - consisting of red sandstones and dolomites, with stromatolites. The belt extends across into Peary Land as a high mountain range. The date of this roughly E-W fold belt has not yet been fixed more definitely than pre-Upper Carboniferous.

The principal zone of interest for this study is the great East Greenland Caledonian belt, which runs N. and E. along the coast for some seven or eight hundred miles. This belt will be dealt with before the stratigraphy of North-west Greenland, and then Ellesmere Island, is discussed.

Nathorst (1901) and NordenskJold (1908) carried out the early investigations, on a large scale; more detailed work includes that by Teichert (1935), Backlund (1930) and Wegmann (1935) on the northern part of the belt; Wordie (1926), Wordie and Whittard (1930), Kulling (1930), and Poulsen (1930) on the southern part, and the summaries by Koch (1929).

Parkinson and Whittard (1931) and Odell have also worked in the central and southern parts.

Wordie has proposed the name Franz Josef Beds for the whole of the sedimentary sequence between the basement complex and the Old Red Sandstones. Considerable argument has occurred on the terminology of the classification within this series, and even on the use of the name 'Franz Josef Beds'. The following scheme seems however, to be the most reasonable, corresponding partly to Wordie's classification and partly to Poulsen's:

FRANZ JOSEF BEDS.	Ordovician	Narwhale Sound Formation. Cape Weber Formation. Cass Fjord Formation. Dolomite Point Formation. Hyolithus Creek Formation.
	Cambrian	Ella Island Formation. Bastion Formation. Spiral Creek Formation. Tillite Canyon Formation.
	? ~~~	
	Eocambrian	Cape Oswald Formation. Eleonore Bay Formation.

(——— indicates disconformity).

The succession in the region of Franz Josef Fjord is best known.

The ELEANORE BAY FORMATION is a much more important and massive unit than any of the other smaller divisions mentioned in the table ~~overleaf~~, reaching over 13,000ft. in thickness. It has been divided by Kulling, into two broad

divisions - the Quartzite Series below, and the Limestone-Dolomite Series above, but Poulson prefers a threefold division, the lower of sandstones and quartzites, the middle of light coloured shales and the upper of limestones and dolomites. The question is rather academic; perhaps Poulson's classification gives a truer picture of the lithological development within the Formation.

The 'quartzite series' lies above even older sediments of this same episode, not yet investigated. It falls into 8 divisions, as follows, the youngest first :-

8.	500 to 650ft.	Reddish-brown shales and some green shales.
7.	200 to 225ft.	Reddish-brown quartzose sandstones. Ripple marks, mud cracks and false-bedding are common.
6.	80 to 100ft.	White quartzites.
5.	330 to 500ft.	Red laminated shales - sometimes red-grey.
4.	650 to 800ft.	Grey-green to white ~~quartzites,~~ in the upper part quartzites, alternating with grey or grey-green shales, or phyllitic quartzites.
3.	980ft.app.	As 4. At the base a thick bed of grey shales.
2.	1300ft.app.	Red quartzites in the centre, pink above and below: ripple marks occur.
1.	1100ft.	Grey-green and white quartzite, the latter often showing beautiful ripple marking: false bedding common. Occasional grey slates with small lenses of dolomite.

Beds below not examined.

Total thickness - 5250 to 5750ft.

The beds pass up into the limestone-dolomite series gradationally, but it is convenient to draw the line of division below a distinctive horizon of alternating red dolomitic slates and grey dolomites.

The detailed stratigraphy of the limestone-dolimites Series is given below:-

25. 130ft. Black limestone breccia - intraformational conglomerate.
24. 325ft. Well bedded dolomite; red green & grey shale beds, and green shale base.
23. 500ft. Dark grey bituminous limestones.
22. 165ft. Light grey dolomite.
21. 330 to 500ft. Grey black bituminous limestone, frequently oolitic.
20. 165ft. Grey dolomite with Cryptozoon.
19. 100ft. Light and red-grey limestone.
18. 500 to 650ft. Dark grey bituminous limestone, often oolitic.
17. 325ft. Red-grey limestone - largely intraformational conglomerate.
16. 500ft. Grey-black bituminous limestone, sometimes oolitic.
15. 650 to 800ft. Light grey dolomite - largely intraformational conglomerate.
14. 500ft. Grey bituminous limestone.
13. 230ft. Light grey dolomite with Cryptozoon.
12.e. 985 to 1150ft. Green to grey-green quartzite.
12.d) 230 (Grey limestone.
12.c) to (Grey quartzite.
12.b) 325ft(Grey dolomite with Cryptozoon.
12.a. 165ft. Green-grey to red-grey quartzite- cross-bedding: slate bands.
11.c. 800ft. Grey dolomite - weathering yellow.
11.b. 165ft. Grey dolomite - weathering grey.
11.a. 230 to 325ft. Grey dolomite weathering yellow, with Cryptozoon.
10. 650 to 800ft. Dark grey bituminous limestone.
9. 500 to 650ft. Distinctly bedded dolomite, banded with red, green and grey shales: with red dolomitic shales in the lower part passing down into the red shales of the quartzite series.

The total thickness of the limestone-dolomite series is thus roughly 8,100 to 9,300ft, and the whole of the Eleonore Bay formation detailed above amounts to between 13,000 and 14,000ft.

Parkinson and Whittard (1931 p.657) give a detailed succession of some 5,090 ft. in the limestone-dolimite series: Cryptozoon reefs in limestone, which alternate with quartzites and shades are again recorded. This work is on an area - Ruth Island - about 30 miles south of the type succession.

The Eleonore Bay Formation contains no rocks which indicate anything other than shallow water deposition. The quartzites in the lower part are cross-bedded, ripple marked, and sometimes show mud cracks. Immensely thick beds of intraformational conglomerates in the higher limestones, the alternation of limestone and sandstone, and the presence of mudcracks on the surface of some bituminous limestone beds - all indicate shallow water. The oolitic portions of the series corroborate this; and highly bituminous limestones, and Cryptozoon reefs indicate the presence of organic life in the basin of deposition. The red and pink quartzites owe their colour to iron oxide pigments and must indicate intermittent silting up of the sea, or uplift of the sea floor into the zone of oxidation and weathering.

The character of the formation taken as a whole indicates rapid deposition in a flat-bottomed trough, sedimentation and downwarping of the floor keeping pace with one another, so that the water remained shallow throughout. The alternation of facies suggests periodic epeirogenic movements of the borderland, and the gradual change of dominant lithology from sandstones to shale, and finally chemical precipitates, indicates a major cycle of sedimentation corresponding to a period in which the borderland, though periodically uplifted, was slowly planed down by erosion. No evidence on the direction of derivation of the sediments, or the position of shore lines, is available : no important breaks in the succession have been recognised.

THE CAPE OSWALD FORMATION lies unconformably above the limestone-dolomite series: it is divisible into two main, but compound, zones, separated by a fluvioglacial series. Several sections of the formation have been described, which serve to show how immensely variable the thickness and lithology are. At Tillite Canyon it is 285ft. thick and consists of 3 tillites, the lowest with humerous, the upper two with few, fragments, the tillites being separated by two horizons of sandstone. Just south of Cape Oswald, on the west coast of Ella Island the thickness is 1750ft. thick, with six thick tillites and five zones of sandstone, shale, or (in one case) black limestone. This latter development

still shows a division into two major parts, for the lower two tillites contain as fragments little but material from the top of the Eleonore Bay Formation - dolomites and limestones : the other tillites, above, have largely igneous and metamorphic material - and few sedimentary fragments. The sandstone-shale sequence between these two parts is well stratified and shows no 'foreign' erratic material : it must be regarded as an interglacial deposit (475ft.thick). In Tillite Canyon the position is rather different : the lowest tillite contains mostly boulders of crystalline rocks, with few of sedimentary material, whilst the upper tillite contain mainly sedimentary blocks - dolomites, limestones, oolitic limestones, quartzites and the like - most of which clearly come from the top of the Eleonore Bay Formation.

The erratic fragments are often well polished, facetted, striated and grooved; they are often rather large. The matrix is almost invariably gritty - consisting of quartz and a little fresh, angular felspar. The sandstone bands which separate the tillites are beautifully false-bedded and are obviously glacio fluvial deposits.

Wherever examined, the tillites of the Cape Oswald Formation rest upon soft dark shales of the Eleonore Bay Formation, which shows no scratching or grooving. The overlying varved shales, these dark shales below, and the general character of the tillites, clearly show that the deposit was formed in shallow water and in very shallow

outwash areas, during a compound period of glaciation, perhaps entailing two major ice advances. The shale series below is about 700ft. thick at Cape Oswald, but over 1600ft. at Tillite Canyon, and the stratigraphy indicates clearly that there is a considerable break between the Eleonore Bay Formation and the Cape Oswald Formation.

The Tillite Canyon Formation follows the tillites, and the lower beds exhibit beautiful varves, quite distinct at the base, but dying out upwards. The beds consist of some 925ft. of dark shales and (in the upper 250ft.) black thinly bedded limestone, with worm casts. The varves are undoubtedly indicative of the continuation of glacial conditions, which steadily decreased in effect.

A marked disconformity separates the Tillite Canyon Formation from the Spiral Creek Formation above. The beds consist of some 80ft. of thin-bedded grey-brown quartzites alternating with red and green micaceous shale - the quartzites show ripple marking, and the micaceous shale - mud cracks and frequent pseudomorphs of halite crystals: these provide good evidence of shallow water, and temporary emergence, with rapid sedimentation.

The lowest of the fossil bearing series is the Bastion Formation which rests disconformably or unconformably on the Spiral Creek Formation. Three sections have

been studied in detail, the localities lying on a north and south line about 10 miles long. In the south on Ella Island, only the upper part of the formation is present - grey-green, glauconitic sandy shales with brachiopods, alternate with beds of grey quartzite. In the north the base is made up of 150 to 200ft. of yellow to white quartzite above which are sandy shales alternating with thin beds of limestone, or sandstone. The limestones contain the majority of the best preserved fossils :-

Lingulella (Lingulepis) sp.nov.
Obolella sp.nov.
Botsfordia caelata (Hall).
Fordilla tryensis Barronde.
Helenia bella Walcott.
Discinella sp.nov.
Helcionella cingulata Cobbold?
Hyolithus (Orthotheca) bayonet Mathew.
Hyolithus (Orthotheca) spp.nov. (3 new species).
Hyolithus (Hyolithus) americanus Billings.
Hyolithus (Hyolithus billingsi Walcott.
Hyolithus (Hyolithus) similis Walcott.
Hyolithus (Hyolithus) sp.nov. (3 new species).
Hyolithellus micans (Billings).
" " var.robustus Cobbold.
Holmia ? sp.nov.
Olenellus cf. reticulatus Peach.

The assemblage is a typical Lower Cambrian fauna, with notable affinity to the faunas of this age of eastern North America-New-Foundland, the Northern Highlands, Scandinavia, and North East Land, Spitsbergen.

Lingulella sp. and Obolella sp. are reminiscent of the Cape Sparre Formation assemblage of Spitsbergen. Botsfordia caelata (Hall) is only known from East and North West

Greenland apart from the areas listed above (N.America, Scotland, Scandinavia): Hyolithellus micans (Billings) has a similar distribution. The variety robustus Cobbold of Hyolithellus micans, and Helcionella cingulata Cobbold, are only known from here in the Bastion Formation, and from Lower Cambrian rocks of Comley, Shropshire, - a rather surprising feature. Fordilla troyensis Barrande and Helenia bella Walcott are only known from E.Greenland and N.America - while three of the Hyolithus species listed occur in N.America, and Hyolithus (Orthotheca) bayonet Matthew occurs also in the Comley assemblage. Olenellus cf. reticulatus Peach indicates correspondence to the Lower Cambrian of the Durness Succession.

Poulsen (1930) who found and described the assemblage believes it to represent the Callavia zone, although the genus Callavia Matthew is not represented in the fauna.

Another slight disconformity separates the Bastion Formation from the Ella Island Formation: 165ft. of thin beds of grey, fairly pure limestones - some developed as intraformational conglomerates, with tiny pebbles of dark limestone; these calcareous beds alternate with fine grained calcareous sandstones, often beautifully cross-bedded.

The assemblage is as follows :-

Problematicum (cfr.Spirocyathus)
Sabellarifex sp.
Kutorgina sp.nov.
Micromitra (Paterina) sp.nov.
Discinella holsti Moberg.
Hyolithellus micans (Billings).
Salterella rugosa Billings.
Paedumias sp.nov.
Holmia ? spp.nov. (2 new species)
Olenellus cfr. reticulatus Peach.
Olenellus spp.nov. (2 new species).
Strenuella sp.nov.
Solenopleura sp.nov.
Corynexochus (Bonnia) cfr.parvulus (Billings).
" " sp.nov.

Again the faunal assemblage shows strong affinity to the Lower Cambrian faunas of eastern U.S.A. and eastern Canada, Newfoundland, Shropshire, Durness, and Scandinavia. The distribution of several of the species has already been mentioned but in addition we have here - Paedumnias Walcott and Corynexochus (Bonnia) parvulus (Billings) otherwise only known from North America: Discinella holsti Moberg is only known from here, and from Scandinavia : Salterella rugosa Billings occurs in North America, Northern Scotland and Shropshire.

The disconformity between this formation and the Bastion Formation cannot be very great for they are both evidently of the Callavia zone, and several species are found which are exactly similar in the two series.

The Hyolithus Creek Formation above may be conformable or not, for the junction is not exposed. The series consists of some 650ft. of massive-bedded, compact, dark grey to

black limestone. No fossils have been found.

Disconformably above the Hyolithus Creek Formation, lies the Dolomite Point Formation - nearly 1000ft. of thinly bedded intraformational conglomerates - consisting of irregular fine-grained light grey dolomite pebbles, in a fine-grained dolomite matrix. Stromatolites of Cryptozoon type occur, but no other fossils.

The Cass Fjord formation rests disconformably above the Dolomite Point formation. It consists of about 1000ft. of soft grey-green shales alternating with limestone beds reaching about 10ft. in thickness. These limestones are intraformational conglomerates.

An 'Upper Ozarkian' fauna has been found :-

Linguelella sp.
Eoorthis sp.
Gasteropod -
Sinuopea ? sp.
Hystricurus ravni Poulsen.
Hystricurus sp.nov.
Symphysurina sp.nov. (2 new species).

The assemblage corresponds very closely to that of the Cass Fjord formation of North-West Greenland, which will be dealt with later.

The Cape Weber Formation rests on a slightly tilted surface of the Cass Fjord Formation. Nearly 2,000ft. of

compact massively bedded dark grey limestone makes up the formation, and the fossils indicate an Upper Canadian age. The break between this formation and the Cass Fjord beds must therefore be considerable - representing Middle and Lower Canadian and perhaps even Upper Ozarkian.

The fauna contains the following :-

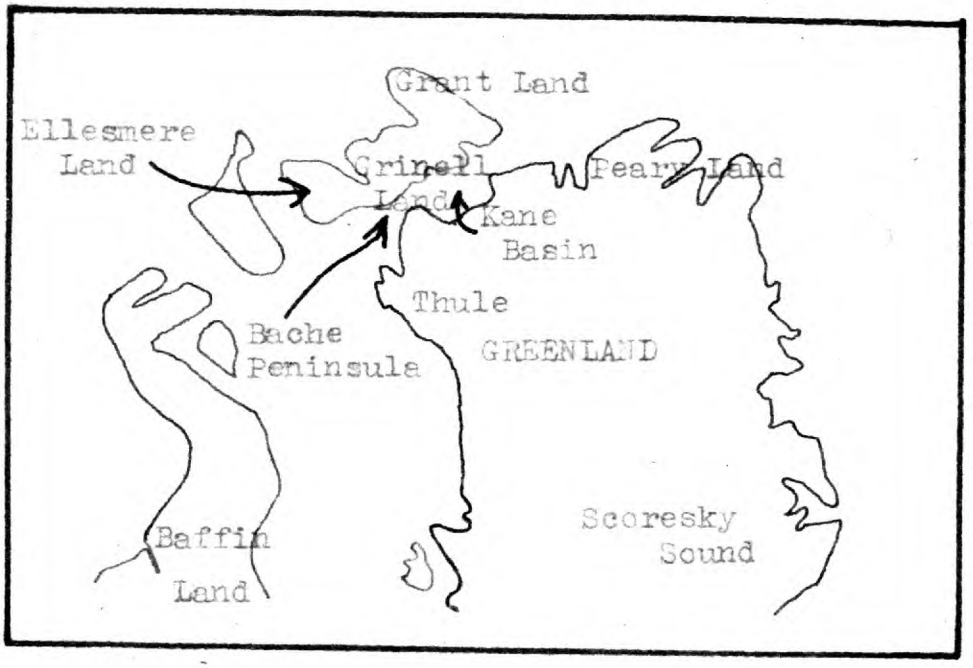
Helicotoma cfr.similis Whitfield.
Lecanospira sp.ind.
Hystricurus sp.nov.
Bathyurellus spp.nov. (3 new species)
Bathyurellus sp.
Petigurus sp.nov.
Bolbocephalus sp.nov.
Cryptozoon stromatolitis.
Unidentified genera of brachiopods, gasteropods and trilobites.

Lange Koch (1929) claimed that the fauna included Maclurites, Endoceras and ?Calspaecia, but Poulsen has re-examined the material and fails to recognise these genera.

The assemblage is of North American type but the large number of new species make it difficult to match very precisely. Bolbocephalus Whitfield is only known from the Upper Canadian (Beekmantown) and the new species found is closely related to Bolbocephalus seelyi Whitfield, from the Fort Cassin beds in Vermont (Beekmantown) : Helicotoma similis Whitfield also belongs to the Fort Cassin beds fauna.

There is a somewhat different fauna of this age in N.W. Greenland, though some genera are common: the point is

D I A G R A M 3 5 .


Grant Land
Ellesmere Land
Grinnell Land
Peary Land
Kane Basin
Thule
Bache Peninsula
GREENLAND
Baffin Land
Scoresky Sound

elaborated later.

The Narwhale Sound formation lies, perhaps disconformably, upom the Cape Weber formation; Poulsen, who made most of these observations, may have overestimated the number of disconformities in this area. The series is about 1,000ft. thick and falls into two divisions, the lower of about 500ft. of thin bedded, light grey, compact limestone - unfossiliferous : the upper 500ft. has a similar lithology but contains fossils, which include Bathyurellus sp. and Ceperditia sp. and some ostracods which it might be possible to use to settle the age more satisfactorily. Bathyurellus Billings is only known from beds older than Chazyan, and the beds overlie Upper Canadian sediments, thus affording two precise limits to the possible age range.

No younger beds, before the Devonian conglomerates, have been recorded in East Greenland: and the Devonian contains no derived pebbles which indicate the former existence of Silurian rocks in this area. The general consensus of opinion is that the most important phase of the Caledonian orogeny in east Greenland was Taconic, and that no Silurian sediments were deposited.

To make this account complete the North Greenland Caledonian belt must be included ; knowledge of this belt comes from work in the areas of Ellesmere Land, Kane Basin and Peary Land :- (diag35)

			ELLESMERE LAND – GRINNELL LAND	N.W. GREENLAND.	E. GREENLAND.
EOCAMBRIAN	ORDOVICIAN	CANADIAN [LOWER ORDOVN.]	UPPER	Cape Weber Formation	Cape Weber Formation?	Cape Weber Formation
				Ostracod horizon	Ostracod horizon
				? Nuna-tami Formation	Gasteropod horizon
				angustifolius hor.	angustifolius horizon
				?	bifidus horizon
			M.		
			LOWER	Cape Clay Formation	Cape Clay Formation
				Cass Fjord Formation?	Cass Fjord Formation	Cass Fjord Formation
			MIDDLE	Blainopsis hor.	Blainopsis horizon
				? Cape Wood Formation	Elrathiella horizon	?
				Glossopleura hor.	Glossopleura horizon
				Oolitic limestone	Cape Kent Formation
			LOWER		Ella Island Formation
				?	Wulff River Formation
					Bastion Formation
				?	? Marshall Bay Formatn.
				Bonniopsis horizon	?	?

EOCAMBRIAN

In the Second Norwegian Arctic Expedition of the "Fram ", 1898-1902, the Cambro-Ordovician beds of the Bache Peninsula were studied and described by Per Schei (1903) and Olaf Holtedahl (1913). The Oxford University Ellesmere Land Expedition, 1934-5, advanced the work in the western part of the zone to its present state (Bentham-1936). The recent large scale Danish Peary Land Expeditions, which have worked for several years since the war in N.E.Greenland under Count Egil Knutt and Ebbe Munck, have contributed most of the present knowledge of the eastern part, since Lange Koch's work (1929-1933). Troelsen (1940) has given the best account of the NW.Greenland Lower Palaeozoic rocks.

In dealing with these areas, it has seemed better to indicate the successions and their correlation to the East Greenland stratigraphy in tabular form (diagram 36), before discussing them in detail.

NORTH GREENLAND will be dealt with first. The Wulff River formation is 90ft. thick in N.E. Greenland, and consists largely of limestones, and sandstones with much glauconite. A basal conglomerate is developed, with small sandstone pebbles.

The Cape Kent formation shows no distinct unconformity at its base, but the lithology and faunal assemblage are markedly different from those of the Wulff River beds. The

thickness is 30ft., consisting of a uniform series of fairly pure oolitic limestones.

The Cape Wood Formation begins with a basal conglomerate with glauconite, and then a series of alternating limestones and calcareous sandstones.

The above three formations make up the Cambrian beds of N. and N.E. Greenland. The Wulff River formation contains Salterella, Olenellus sp. etc., and the Cape Kent limestones contain Olenellus, Kochiella, and Inglefieldia; these two formations are both, therefore, of Lower Cambrian age. The Cape Wood Formation contains Glossopleura, and Clavaspidella, etc., and is of Middle Cambrian age. It is thus clear that large stratigraphical breaks exist here, not only at the base of, and within, the Lower Cambrian, but also between the Lower and Middle Cambrian, and above the Middle Cambrian, - for the whole of the Upper Cambrian is missing,-a very significant feature in our consideration of the broader relationships of these sediments to those of other areas.

About 1,800ft. of Lower Ordovician sediments lie above the Middle Cambrian beds. The Cass Fjord Formation is nearly 1,300ft. thick, and consists of argillaceous limestones, limestone (intraformational) conglomerates, and soft shales. The fossils indicate a lowermost Ordovician age; they include the brachiopod Eoarthis, the gasteropod Sinuopea, and Hystricurus.

The Cape Clay Formation, disconformably above, consists

of 100ft. of limestones. The fossil assemblage again indicates a Lower Canadian age; with Eoarthis, Ozarkispira, and Hystricurus, and the trilobate Symphysurina.

The Nunatami formation, 450ft., consists of shales and limestones, often as intraformational conglomerates. It is rich in fossils - some graptolites, eg. Phyllograptus sp. and Didyimograptus bifidus, indicate the precise age of various horizons (see table, diag 36 p. 243). Trilobites - Bolbocephalus, Goniotelus, and Isoteloides - are also present. The age of the formation is Upper Canadian, and the Middle Canadian is therefore absent from Greenland entirely.

In PEARY LAND the sequence is even less complete. The Cape Kent limestones are missing, and so is the Cape Wood formation. Sediments with the characteristic fauna of the Wulff River formation are followed unconformable by the Upper Canadian; the Cass Fjord Formation and the Cape Clay Formation of the Lower Ordovician are missing. So the Upper Cambrian, Middle Cambrian and Upper Lower Cambrian are absent in Peary Land, as well as the Middle and Lower Canadian.

The Lower Palaeozoic Series here is underlain by a thick series of sediments, the Thule formation, which includes beds of tillite - this time resting on scratched rock surfaces. Little is known of the formation here, and nothing seems to have been published in any detail.

To the West, north of Thule, the Thule formation again underlies the Lower Palaeozoic rocks, and is here made up of sandstones and dolomites; with tillites. The atratigraphy has not been worked out but there is certainly a strong suggestion that these sediments are the equivalent of the Eleonore Bay formation of east Greenland.

In ELLESMERE ISLAND Lower Cambrian rocks rest on a peneplained surface of Archaean rocks. Per Schei (1903) and R. Bentham (1936) have worked in the area, and the palaeontological material has been studied and described by Poulsen (1946).

The stratigraphy is not perfectly known, but the broad divisions and relationships are shown in the table.

The Bonniopsis horizon is the oldest fossiliferous bed in the region : its equivalent has not been identified in N.W. Greenland, but there, in the Wulff River formation, occur pebbles with Acrothele? pulchra (and Paterina lata) - species from the Bonniopsis fauna, which suggests that the horizon was in fact also laid down E. of the Kane basin, but subsequently eroded, before the deposition of the Wulff River formation. The limestones of the horizon contain:-

Acrothele? pulchra Poulsen.
Hyolithes (Hyolithes) sp.
Paedeumias? borealis sp.nov.
an Olenellid-unidentified.
Bonniopsis nasuta gen. et sp.nov.
Bonniopses rostrata sp.nov.

The Marshall Bay Formation may be represented here in a sandstone, grit and conglomerate series : in 1940 Troelsen described its discovery in NW Greenland - and it is given in the table, dated by Olenellid trilobites : details of its lithology are at present unfortunately confined to descriptions in Danish - Troelsen (1940).

The Wulff River Formation of NW Greenland has not been identified W. of the Kane Basin, but Poulsen, for example, suggests that it may form part of the unfossiliferous conglomerate, sandstone and grit series mentioned above.

Troelsen records an unfossiliferous limestone above the Bonniopsis horizon at Bache Peninsula : this limestone, (oolitic) he regards as the Cape Kent formation.

The Cape Wood Formation represents the Middle Cambrian - limestones, often sandy, are part of the formation, but the stratigraphy of all these groups is virtually unknown. Fossils have been collected from various localities, and the presence of rocks is inferred from the occurrence of faunas of various ages. The fossils recorded here are evidently referable to three horizons, the lowest the Glossophura horizon, with a Clavaspidella limestone formerly regarded as a distinct horizon (Cape Frederik VII formation of Poulsen, 1927) in its centre (Troelsen, unpublished); a central, Elrathiella horizon, and an upper Blainiopsis horizon.

The Glossopleura horizon includes :-

Clavaspidella ? sp.
Glossopleura cf. expansa Poulsen.
Glossopleura longifrons Poulsen.
Glossopleura Walcotti Poulsen.

The Elrathiella horizon includes Elrathiella obscura Poulsen.

The Blainiopsis horizon includes :

Blainiopsis benthami gen. et sp.nov. ~~(Gen.et sp.nov).~~
" holtedahli sp.nov.
" scheii sp.nov.
" ? sp.
Elrathia ? sp.
Kochina arctia sp.nov.
Olenoides ? fallax sp.nov.

The presence of Kochina Resser suggests Middle Cambrian age, and the whole of the Upper Cambrian is thus missing.

The Cass Fjord formation is only identified by the lithological similarity of a single specimen brought back by Bentham.

The Cape Clay, the Nunatami and the Cape Weber formations have however been recognised, but two horizons of the Nunatami formations have not been identified, due to the absence of Didymograptus bifidus, and the gasteropod horizon.

The Cape Clay beds include :-

Clarkoceras sp.

The Nunatami formation includes :-

Pomatatrema semiconvexum (Poulsen)
Eccyliopterus ? sp. indet.
Raphistomina latiumbilicata Poulsen?

Spyroceras? sp.indet.
Cybelopsis speciosa Poulsen.
Isoteloides? polaris Poulsen.
- Asaphid trilobite - Gen. and sp.indet.
Goniotelus crassicornis Poulsen.
Bolbocephalus glaber (Poulsen).
Goniotelus bggildi (Poulsen).
Isochilina suavis Poulsen.
" perporosa Poulsen.

The Cape Weber formation includes :-

Archaeorthis groenlandica Poulsen.
Helicotoma ? sp.indet.
Hormotoma ? sp.indet.
Maclurites sp.indet.
Actinopeltis feildeni gen. et.sp.nov.
Hystricurus crassilimbatus Poulsen.
Isochilina suavis Poulsen.

Mixed collections of faunas from both Nunatami and Cape Weber formations include, as well as the above,

Phyllograptus sp.
Raphistomina latiumbilicata Poulsen?
Bathyurellus teicherti Poulsen.
Petigurus sp.
Poltyoccia borealis) associated with a bathyurid -
" multicamerata) gen.et sp.indet.

FAUNAL AFFINITIES.

The faunal assemblages of Greenland as a whole have affinities with those of various areas of Lower Palaeozoic sedimentation - Spitsbergen, N.W. Scotland, Scandinavia, Shropshire, Newfoundland, and more especially N.America. The evolution, migration and distribution of the Lower Palaeozoic faunas - with relation to Greenland particularly - has been considered by Koch, Ulricht and Poulsen, and their

DIAGRAM 37.



conclusion is that there are definite affinities between the Greenland assemblages and those of the St.Lawrence Geosyncline on the one hand, and the Cordilleran Geosyncline of the west coast on the other. Poulsen, dealing with North Greenland more particularly, indicates that the Wulff River formation has faunal affinities with both the Cordilleran and the St.Lawrence East Greenland areas. The Cape Clay fauna is related to assemblages from the Cordilleran geosyncline; Koch considers that the formation in East Greenland shows invasion by faunas from the north. The Ordovician faunas on the other hand seem to indicate distribution from the St.Lawrence geocyncline to North Greenland, via the east coast.

Poulsen's view of the general Lower Palaeozoic palaeogeography, for example in Upper Canadian times, is something like that shown in diagram 37, (opposite)

Little has been said concerning the Lower Palaeozoic part of the succession with regard to its mode of deposition. The essential facies are sandstones and conglomerates on the one hand, and limestones or dolomites on the other. The sandstones show all the characters of shallow water deposition: the conglomerates overlie unconformities and are obviously due to emergence of the sea floor: the subordinate shales, which occur more particularly in the Ordovician, sometimes

contain Graptolites and are evidently mostly of the graptolite shale facies - the current view being that these are rather deeper water deposits, compared with the sandstones. The limestones are often oolitic and very often occur as intraformational conglomerates, which indicate frequent, if not permanent, shallow water conditions. The succession is markedly characterised by stratigraphical breaks : the thickness of beds between successive disconformities is rarely very large. Large parts of the succession are missing - some of them due to non-deposition, some to subsequent erosion before the succeeding formation was laid down. The whole of the Upper Cambrian is missing, and of the Ordovician only the Canadian is represented.

Clearly the rocks were laid down in areas where sedimentation kept pace with the downwarping over certain periods. Conditions however were much less stable than in the Eocambrian period, and positive movements often brought the areas above sea level; or after peneplanation, the borderland was not rejuvenated for some time and in the interval a stratigraphical gap, or a condensed sequence was formed.

CONCLUSIONS.

We may summarise the Caledonian of Greenland briefly as follows :-

The Precambrian crystalline rocks are overlain by a thick series of rapidly deposited sediments (the Eleonore Bay Formation of E.Greenland, the Thule formation of N.W. Greenland) which give way to dolomites, in the upper parts of which are marine tillites: (the Cape Oswald Formation and the Tillite Canyon formation of E.Greenland, and the Thule tillites of the north-west.) The characteristics of these tillites, namely that their boulder material is derived from slight upwarping of the beds below - (dolomites in each case), -that they were laid down in water, - that two main phases may be distinguished, - that the beds above are also dolomitic, - all these characteristics are seen in the tillites of the Sveanor Formation and the Tanafjord tillites, and to a slightly less precise degree in the tillites of southern Norway, and Scotland. The evidence convinces the writer that all these tillites are the result of the same glacial epoch and that it is justifiable to use them as time markers to correlate the successions, in the absence of fossils.

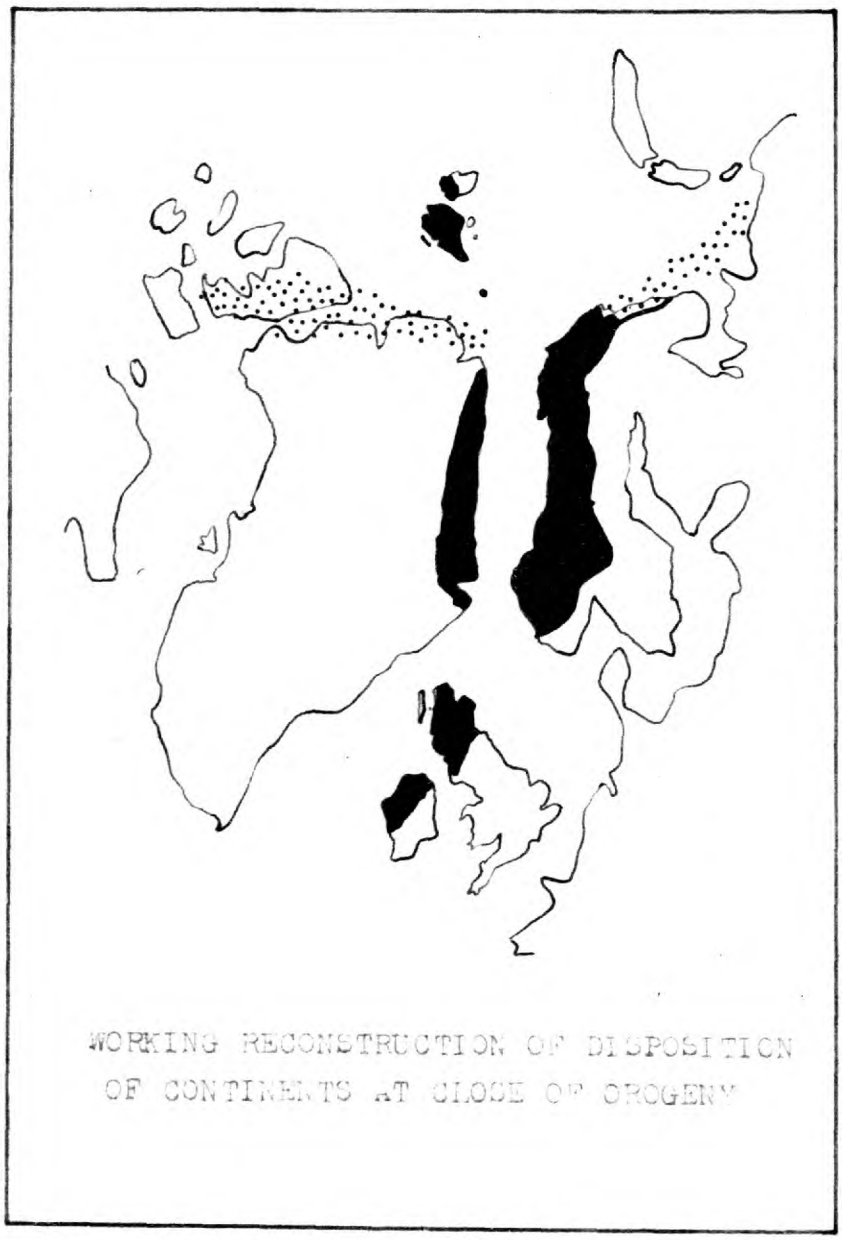
The upper part of the Eleonore Bay Formation of Greenland leads to the Cambrian, with disconformity. This shows the same progressive change of lithology from land detritus to carbonate rocks as in the N.W. Highlands, and the Middle and Upper Cambrian similarly are missing in N.E. Greenland.

Poulsen claims to have mapped the six lithological groups of the Durness limestone as such, in this Greenland area.

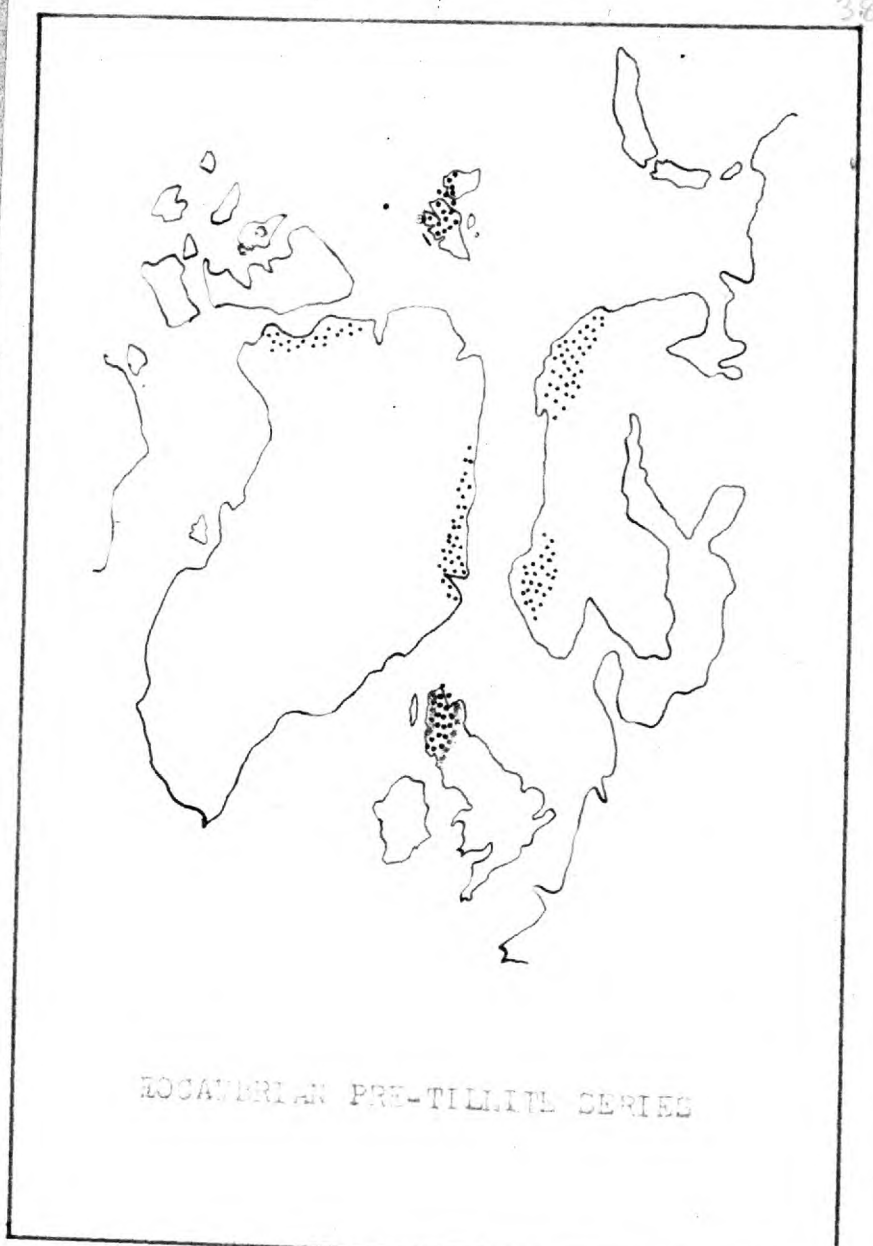
The faunas of the Lower Cambrian (page 237) correspond very closely with those of the N.W. Highlands (page 219). The Canadian faunas of Greenland are even more closely related to those of the Durness Limestone (page 220), and to those of the Younger Dolomite Series of Bear Island (page 180).

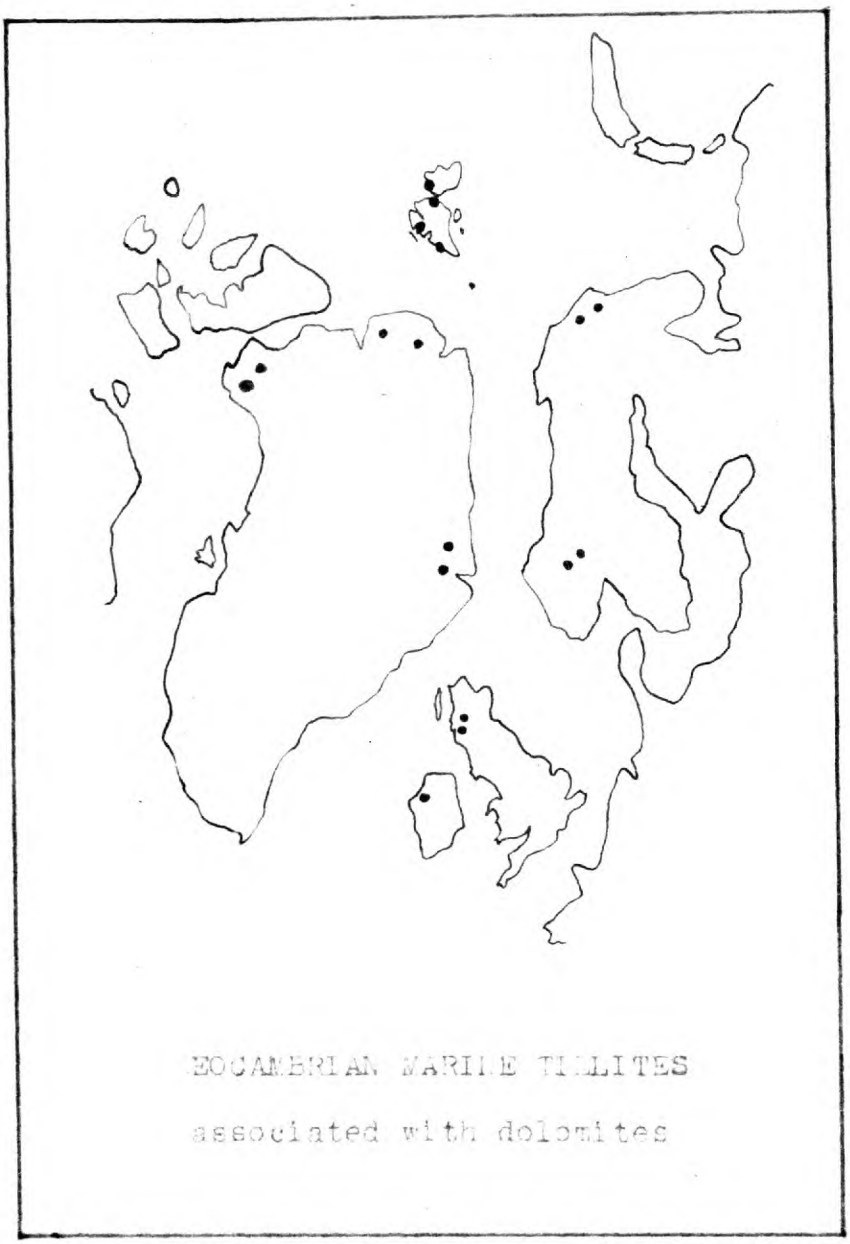
Extensive deposits of Old Red Sandstone cover the main fold belt, in which- as in all the other areas - no evidence of the deposition of any rocks later than Lower Ordovician can be seen.

The maps which follow present some of these features of correspondence between the rocks of Greenland and those of the rest of the Caledonides of the North Atlantic - Arctic province. They indicate that a great many aspects of the Caledonides are more readily understood if drift of the Continents is admitted to be a possibility.



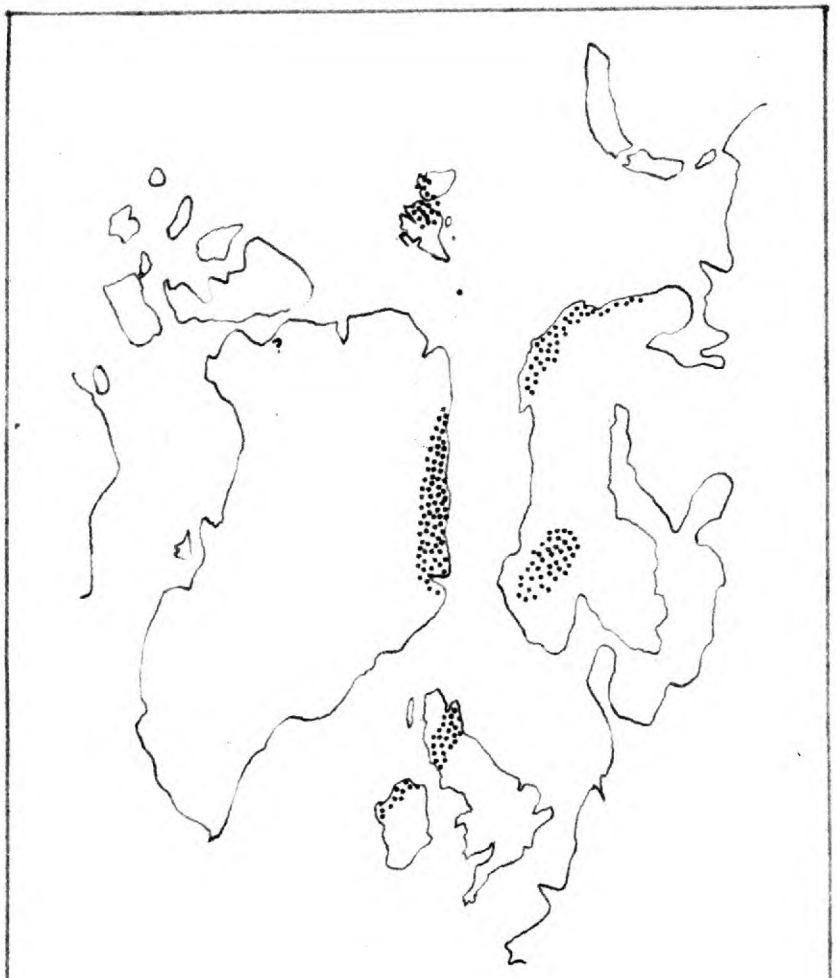
WORKING RECONSTRUCTION OF DISPOSITION
OF CONTINENTS AT CLOSE OF OROGENY


38
ECAMBRIAN PRE-TILLITE SERIES



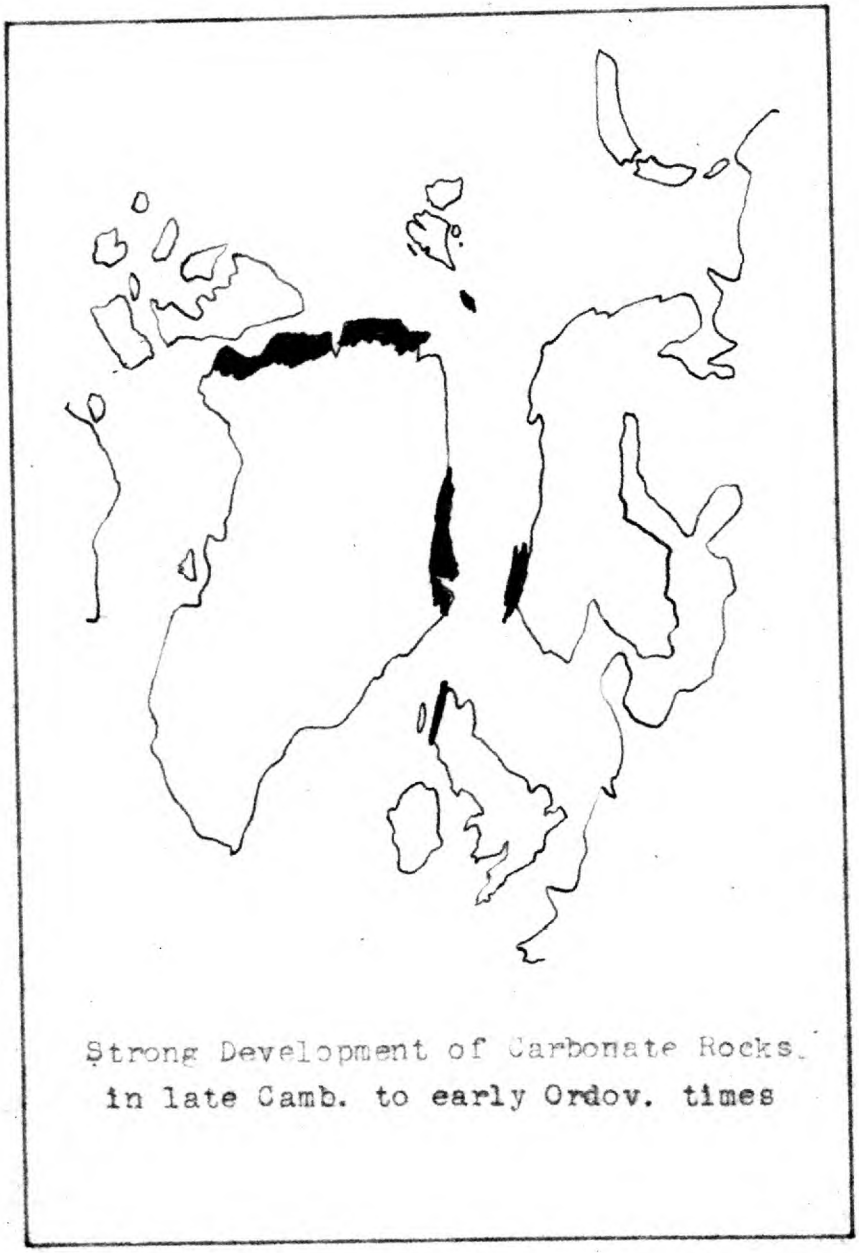
EOCAMBRIAN MARINE TILLITES

associated with dolomites

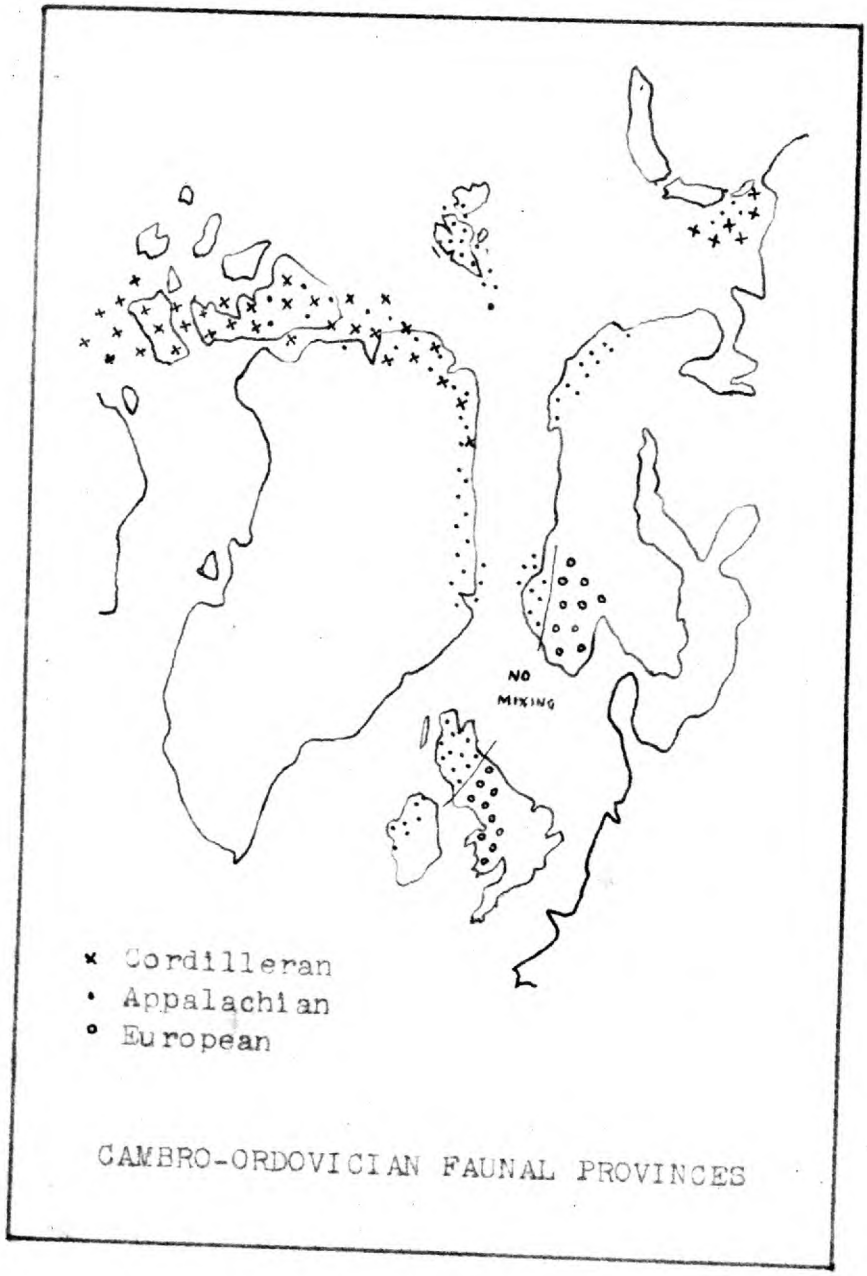


POST-TILLITE SERIES

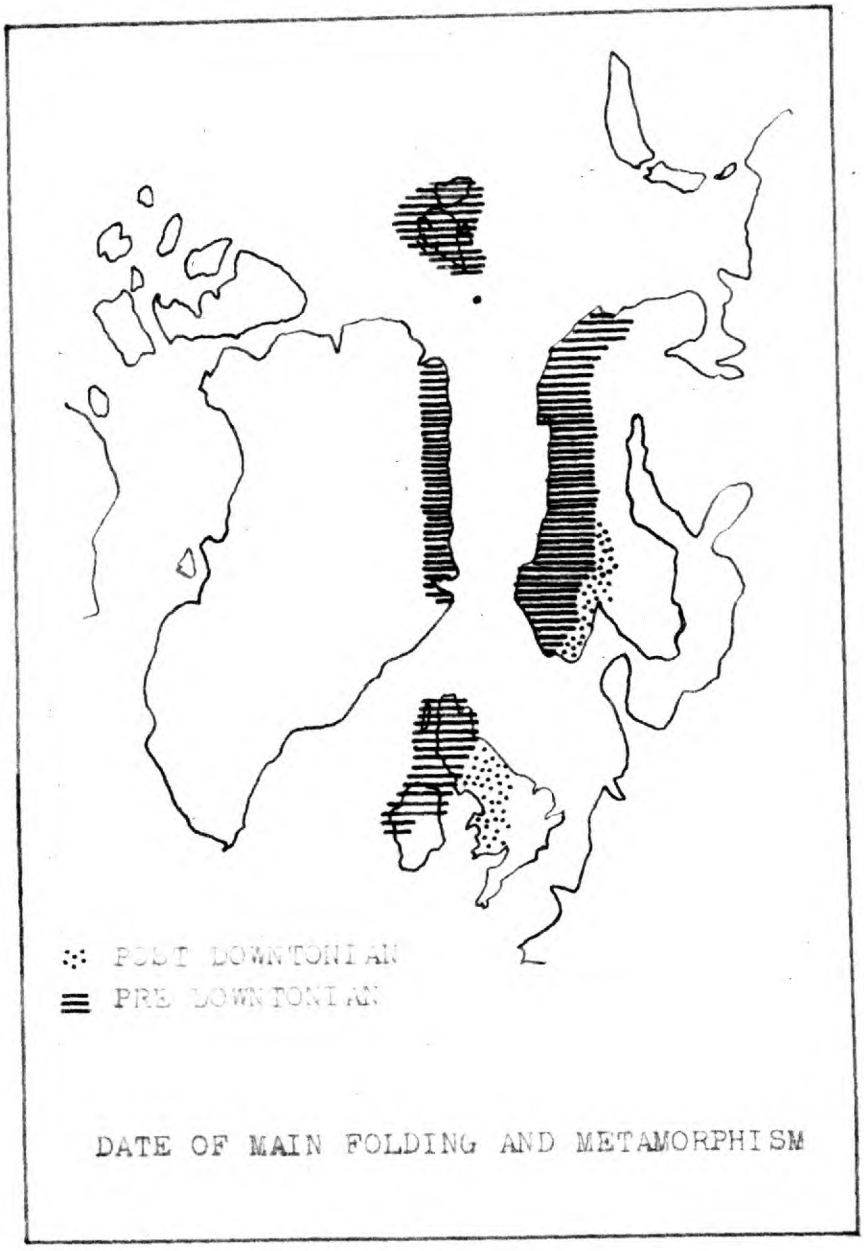
Eocambrian passing conformably into fossiliferous rocks.



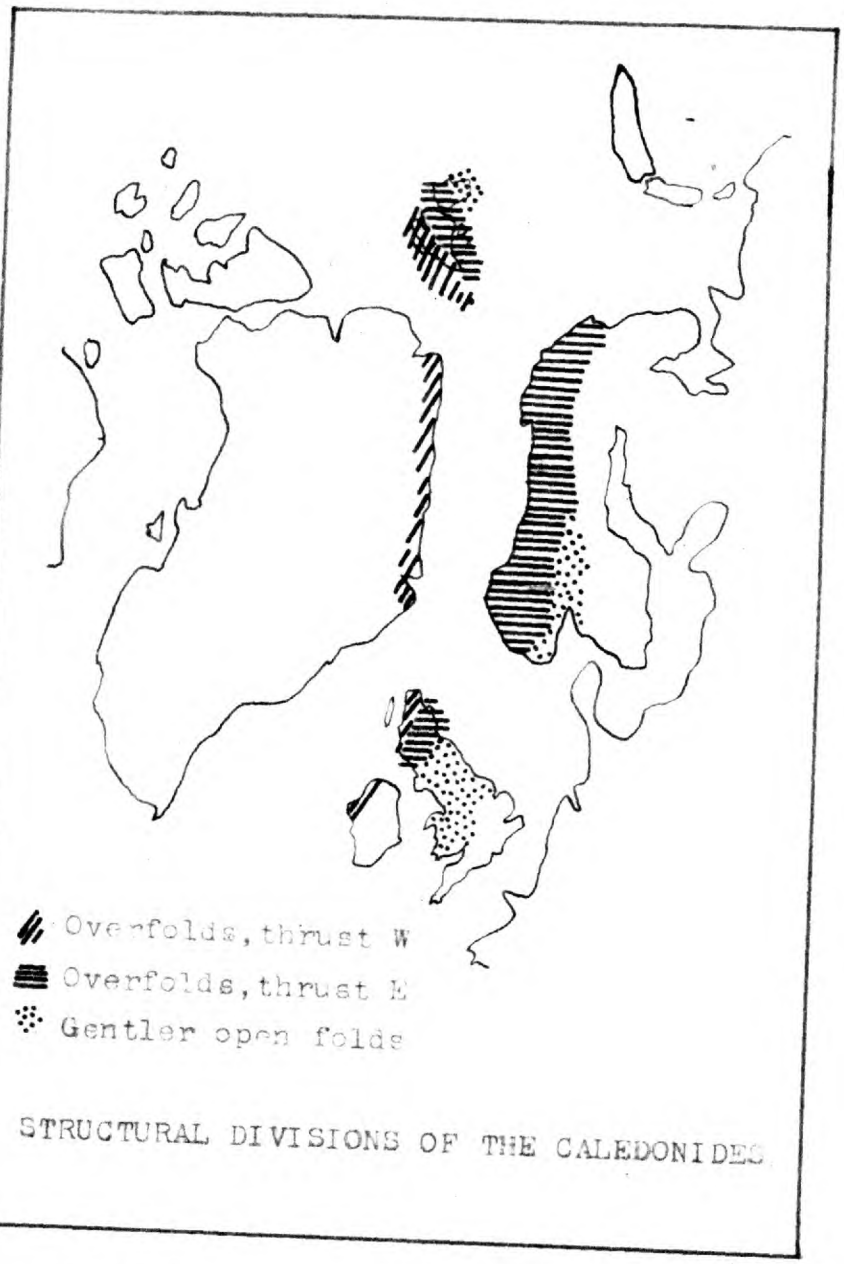
Strong Development of Carbonate Rocks.
in late Camb. to early Ordov. times



CAMBRO-ORDOVICIAN FAUNAL PROVINCES



DATE OF MAIN FOLDING AND METAMORPHISM

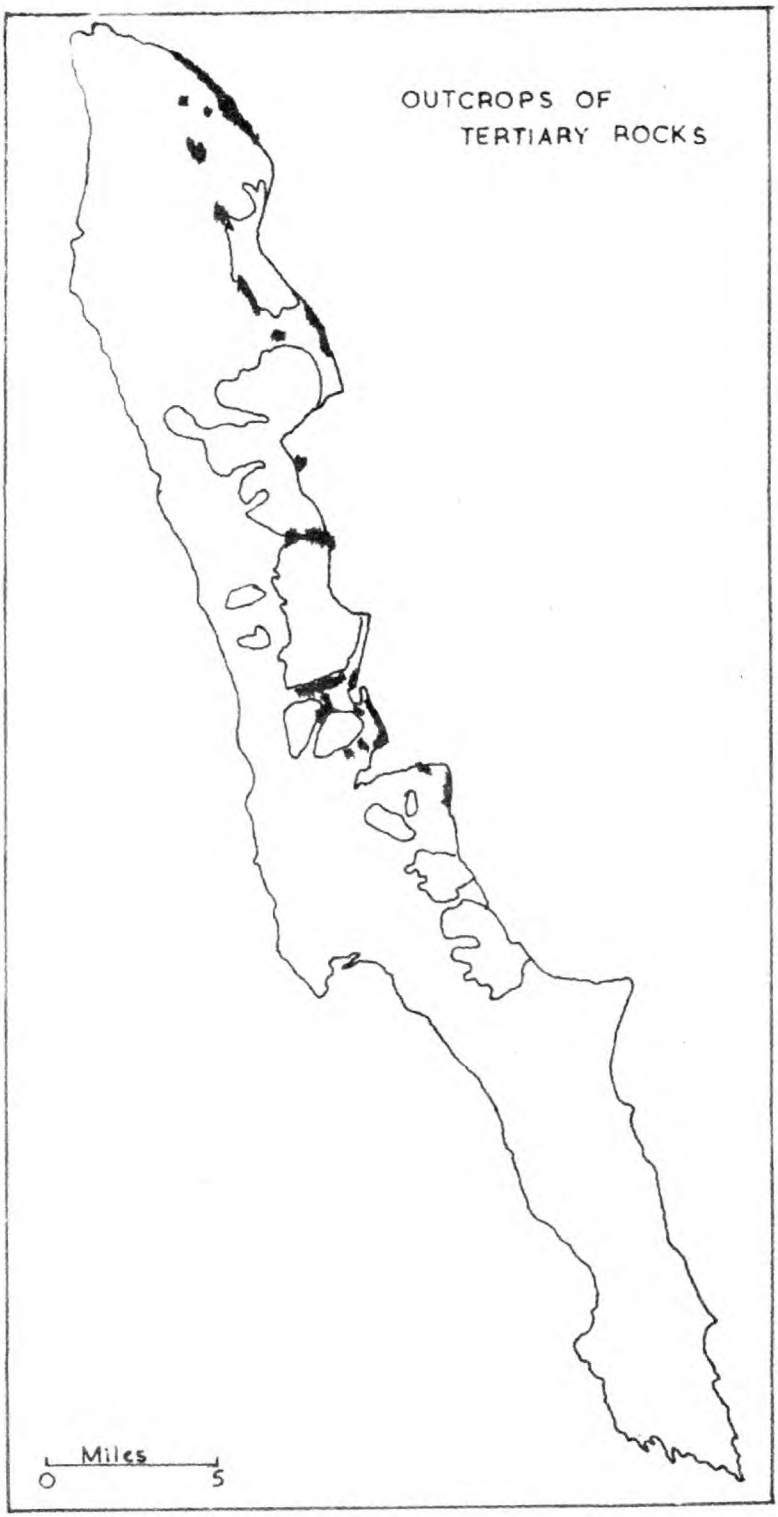


STRUCTURAL DIVISIONS OF THE CALEDONIDES

PART III

THE TERTIARY ROCKS

DIAGRAM 45.



INTRODUCTION.

The areas in which Tertiary rocks crop out at the surface are indicated in the diagram opposite; the rocks are conglomerates, sandstones and black shales. Fossils are poorly preserved, collections having so far failed to indicate the age of the beds precisely.

The deposits are extremely variable, consisting of rapid alternations of the sediments mentioned above, a bed of any one rock-type rarely exceeding 10ft. in thickness. Apart from the development of a thick basal conglomerate, there can be no scheme of stratigraphy relating the beds of the various outcrops: successions have been measured, but the lithology shows too much small scale variation and no major divisions emerge.



Plate 27. Typical coastal exposures of Tertiary rocks.

SEDIMENTARY PETROLOGY.

The basal conglomerate of the series is seen on the north side of Selvagen, and in the area between Geddesfjellet and Krokodillen (see map C). The actual unconformity is only exposed in one place, at a height of 450ft, 1,270 yards west of Reinhardpynten. Boulders here reach 3ft. 6ins. in maximum dimension, consisting of large slabs of Hecla Hoek quartzites and schists, and a great deal of green slaty material obviously derived from the beds of the Larsen group in the immediate neighbourhood. The sorting is extremely poor - blocks of all sizes being piled together. There are sudden intercalations of thin bands in which the broken slaty matter is the sole component. These bands are between 1ft. and 3ft. thick and are immediately followed by the reappearance of huge blocks. The corners of some of these are fairly well rounded, but many retain the rectilinear shape produced by jointing. Higher in the conglomerate, huge blocks become less common, and the matrix is more sandy, with the slatey Larsen group material more fine-grained. The change is not a steady one, however, for upon it are superimposed immense variations in the coarseness of the conglomerate, the occurrence of bands with huge blocks persisting throughout. There is no sign of stratification apart from the occasional finer intercalations.

On Geddesfjellet the basal conglomerate forms the dip slope of the east face of the mountain. Towards the base of the series (the unconformity is scree covered) blocks as large as 4ft. cubes are seen, the blocks being white, pink and grey quartzites, schists, greenstones and slates: the matrix is a red or green grit. Again fine intercalations (of sandstone-grade) are common.

The basal conglomerate shows very poor sorting. Sedimentation must have been extremely rapid and transportation was evidently over only a short distance in the case of the larger blocks, and almost no distance in the case of the slaty material: the enormous size of the blocks must indicate extremely violent transport. Sudden intercalations of finer bands indicate that influx of coarse material was sporadic, and must mean that the energy of the transporting agency was extremely variable, as a result of instability either in the source area or in meteorological conditions. Violent outflows from a sporadically rising mountainous borderland may be inferred, the deposits being dropped 'en bloc' in the flood-plain area where velocity was suddenly checked. Within the conglomerate there is evidence that the direction of derivation was from the west. Pebbles are frequently piled 'en echelon' at a small angle to the stratification ~~—the sketch opposite illustrates this point.~~ Further, the thickness of the conglomerate rapidly increases

to the west - being 200ft. thick two-thirds of a mile west of Reinhardpynten, 500ft. thick one and a quarter miles further west - a change of 240ft. per mile (see profile C6). The conglomerate at Geddesfjellet must be about 400ft. thick, so the direction in which the formation thins most rapidly is roughly due east. The conglomerate in that direction becomes much more fine-grained than in the west - pebbles are far more rounded and rarely reach over 1ft. 6in. Fine gritty bands are more common, but the whole deposit still shows very poor sorting.

Throughout the rest of the series there is no gradual lessening in the frequence of conglomeratic bands; instead there is rapid variation in grade from conglomerate to shale, with rarely any consistent sedimentation of one rock-type over a long period. A typical part of the succession near McVitiepynten is as follows :-

	7in.	silt.
	4ft.	sandstone.
1ft.	9in.	conglomerate.
	3in.	shale.
7ft.	-	sandstone.
4ft.	-	conglomerate.
4ft.	-	sandstone.
	5in.	silty shale.
1ft.	6in.	sandstone.
	4in.	shale and silty shale.
2ft.	-	conglomerate.
	2in.	silt.
6ft.	7in.	sandstone.
1ft.	-	silt.
	6in.	sandstone.
	5in.	silt.
6ft.	-	sandstone.
2ft.	6in.	conglomerate.

	4in.	shale.
2ft.	-	conglomerate.
3ft.	-	coarse conglomerate (with 6in.pebbles)
2ft.	-	finer conglomerate.
	6in.	shale and silty sandstone.

This intricate variation in grade size could hardly be due to changes in distance from the shore line or in depth of water. It is clearly a result of sporadic variations in the power of the transporting agent. It is hoped to show that certain features in the rocks themselves indicate that this variability is due to repeated small positive movements in the land area to the west.

Representatives of each of the rock types from different parts of the island are indistinguishable. The conglomerates vary tremendously in their coarseness, but are mostly quite fine-grained, pebbles averaging lin. or 2in. in diameter. Usually the corners are quite well smoothed, but attrition has rarely produced anything near a perfect ellipsoidal shape. The matrix is usually light grey and gritty, but often slightly finer, black, and carbonaceous.

Specimen 952 from south of Selvagen, near the hut at Kenmore, has an average grain size of 1 mm, the well rounded pebbles reaching nearly 20 mm. in diameter. The grains are generally of quartz - greatly strained - but most of the larger pebbles are of fine-grained quartzite and decayed schist fragments.

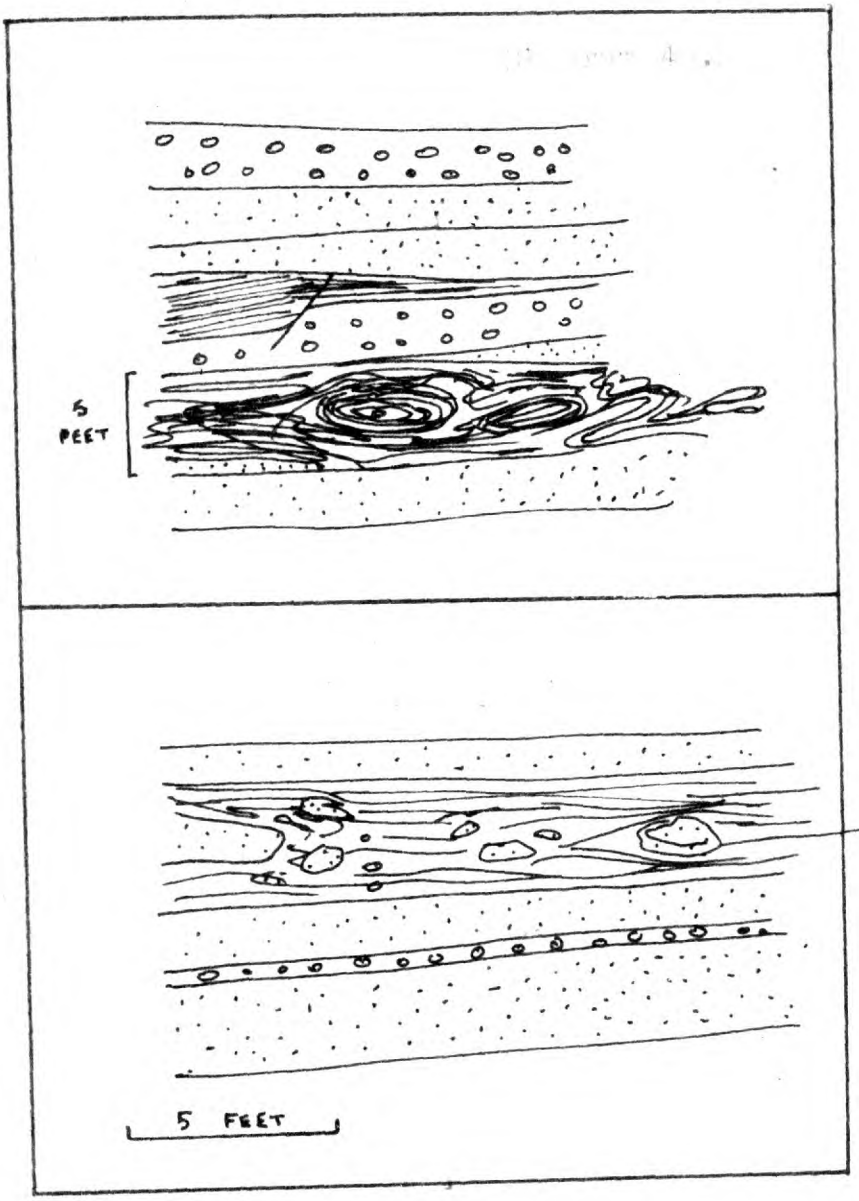
Slide 1205, of a fine conglomerate from Buchananryggen, shows pebbles averaging 3 mm, but reaching a maximum of 7 mm: they are composed of fine to medium-grained quartzites, phyllites - (often puckered), and mylonites and brecciated rocks similar to those of structural unit 4 of the central range. Slide 324, a conglomerate from the east end of Balfourfjellet, shews particularly bad sorting. The matrix is entirely siliceous, with a few tiny schorlite grains: pebbles average 2 mm, the grains in the matrix, about 0.1 mm.

Extremely bad sorting, and lack of stratification is again shewn in slide 76 (from the coast north of McVitiepynten). The size of components ranges from 15 mm. to 0.5 mm. or less.

The sandstones are all compact slabby grey or brown rocks, weathering brown. There are all grades of variation, to conglomerates, and to silty shales, but slide 950 is an average example. Half the grains are of quartz, half of decayed rock fragments - phyllites and slates, extremely dirty looking in thin section : accessory schorlite is also present. The grains average 0.4 mm. and are rarely larger - but there are numerous grains below that size, ranging down to 0.05 mm: all are very angular. Slide 339 (from close to the graben fault east of Barentsfjellet) shows similar features - an average grain size of 0.4 mm; about 30% of the rock being quartz grains and 70% decayed rock

Plate ~~28~~ 33





fragments, notably fine-grained limestones and green slates similar to those of the Barents group. A coarse sandstone from Buchananryggen showed the usual poor sorting, grains varying from 1.2 mm. to 01. mm - 50% of quartz, 50% of weathered micaceous rock fragments. Schorlite is an accessory.

The shales are invariably black, though not notably carbonaceous. Blebs of bright coal, obviously of drifted origin were seen in one locality on the coast one mile north-west of McVitiepynten, small lenses reaching 3 cm.x 3cm.x 0.5cm; and some rather carbonaceous shales were seen in other areas. The shales are usually silty - slide 953 from near Kenmore contains 60% irregular quartz grains, of an average diameter of 0.1 mm. or less. The rest of the rock consists of stained and decayed micaceous rock fragments. Slide 1143 from Buchananryggen has a fine-grain size, but occasional fragments of 0.3 or 0.4mm. occur. 20% of the rock is quartz, the rest a fine clay material.

The variable lithology of the Tertiary rocks suggests extreme instability. Were the forces which produced the graben and horst structure of the Foreland and Foreland Sound already in operation?

In the coastal exposures north of McVitiepynten at several localities, violent deformations are seen. A shale-

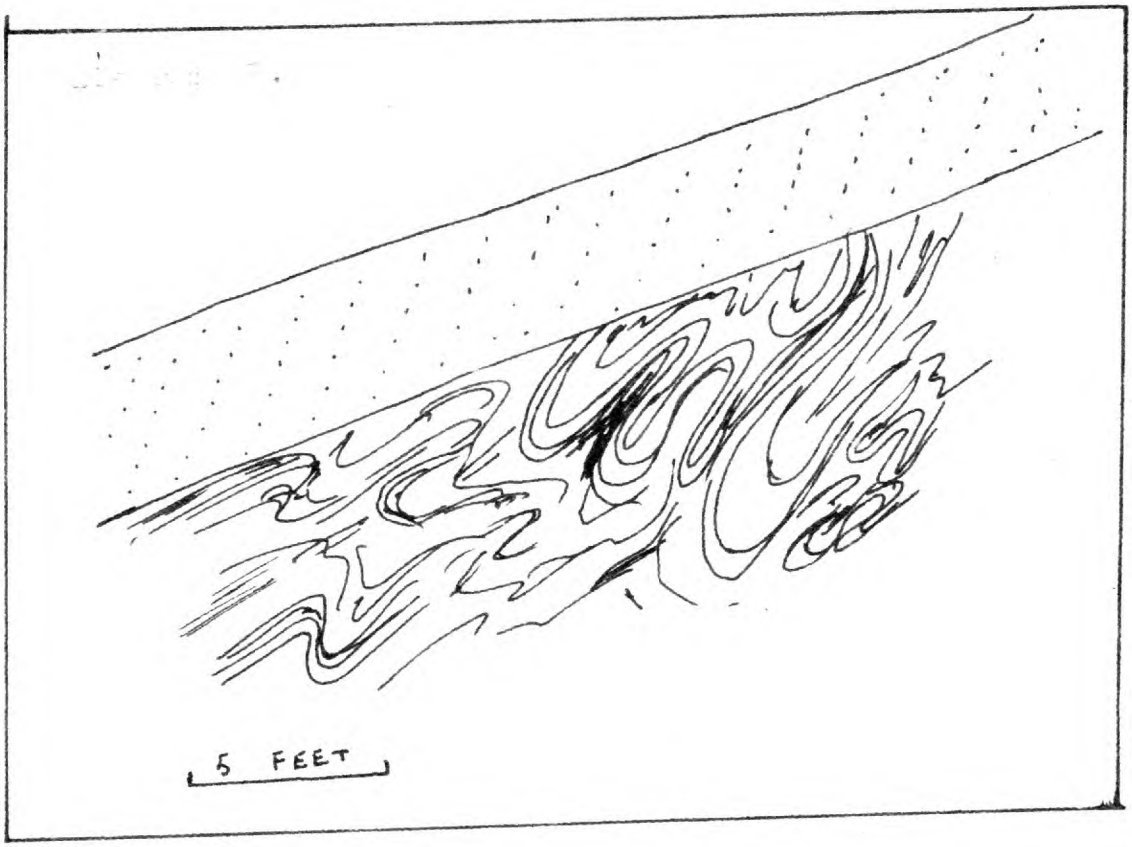




Plate 34.

Plate 35.



ball 3ft. across is shewn in plate 28 33 ~~opposite~~, and the sketch below it illustrates numerous similar features appearing in the same 5ft. bed of shale. The undisturbed sandstones and conglomerates which overlie it demonstrate that the deformation is contemporaneous with deposition. The second sketch is of a disrupted sandstone bed about 20ft. higher in the succession: the fragments are surrounded by silt.

Some deformation features seen have been produced by the sliding of slabs of sandstone over shales - others are apparently free slumping structures. The third sketch (diag. 47) and the accompanying photographs, plates 29 34 and 30 , show an example of intricate deformations in an 8ft. shale band, truncated by the undisturbed sandstone band above. Obviously the top of the distorted shale was eroded before the sandstone bed was laid down.

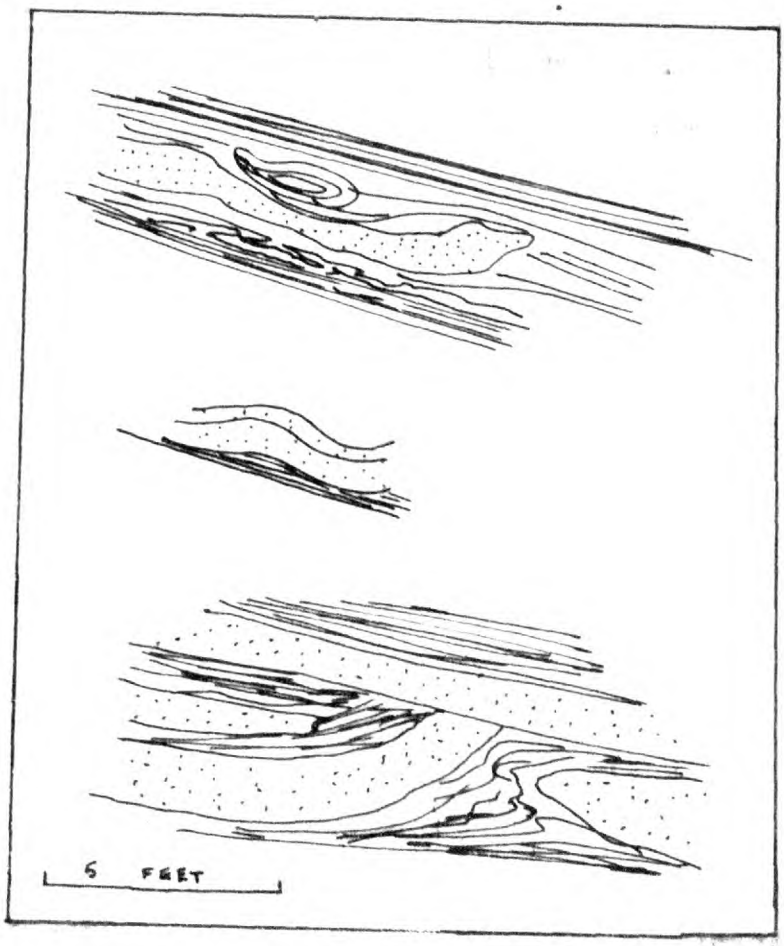
Plate 31 shows another common feature in these rocks - a band thins out in a short distance to nothing, with no distortion of the beds above. Shales and silts are sometimes lensed out by the sliding of slabs of sandstone: Other cases represent small disconformities. Occasionally angular disconformities of as much as 17° are seen.

Phenomena precisely similar to those described above may be seen in the coast sections near Reinhardpynten. The sketches (diagram 48) show a few examples.

Each of the deformation features which have been described shews by its attitude the direction of the movements



Plate 36.



which produced it: an indication of the direction of slope of the sea floor. There is a wide variation in this direction, but it averages about 20° north of east, and all readings have an eastward component.

Conclusions.

The basal conglomerate becomes thinner and less coarse in an eastward direction. This fact and the alignment of pebbles, clearly demonstrate derivation from the west: the coarseness of the rock, its composition and the lack of rounding and sorting, indicate a very short distance of transport.

The sediments throughout the series tell of extreme instability in the source area. Contemporaneous deformation indicates periodic slumping and sliding under gravity towards the east.

The conclusion is drawn that the graben and horst structure of the Foreland had already begun to develop, whether as a flexure, or by actual displacement on a fault or faults. The Tertiary rocks probably never extended far to the west of their present outcrop. Though the date of these sediments is not known exactly, they do not correspond to any of the successions of the central syncline of Spitsbergen. It seems clear that no correlation can be expected, and that these rocks may well belong to a separate

trough of deposition altogether. This is speculation, however, in the absence of data from the other side of the Foreland Sound. It will be confirmed if there the rocks are found to be derived from the east, and slumping structures indicate reciprocal downward movements towards the Foreland Sound.

PALAEONTOLOGY.

Definite fossil remains were found in three localities only and then in a state of only poor preservation.

The strip of Tertiary rocks on Buchananryggen, which separates the thin faulted wedge of Hecla Hoek rocks from the main outcrop to the west, yielded a foraminifer in one of the thin sections of a silty shale. This was identified as Cyclammina sp., unfortunately of no use in precise dating. This is the only slide which has shewn any signs of the preservation of foraminifera, but protracted work might yield results, and this is perhaps the line of research most likely to succeed in dating the rocks.

The second locality is the 1200ft. top of the hill at the east end of Sesshogda, where a small plant cone was found, about 1mm. in diameter, preserved as an impression in black shale.

The chief fossil locality is on the north shore of Selvagen. Vague impressions of plant remains can be seen intermittently in the rocks of the shore and the sea cliffs from Reinhard-pynten westward to the point where the basal conglomerate is reached. The best preserved specimens were found at a point 2,160feet west of Reinhardpynten, that is some 60yards beyond the mouth of the stream which flows south-eastward into the haven from the end of Sesshogda.

Mr. W.N. Edwards of the British Museum (Natural History) most kindly examined the plant material, but reported that almost all the remains are too fragmentary to allow precise identifications. However among the dicotyledonous leaves is represented Corylus macquarrei, of a type found in other early Tertiary floras from Arctic regions. Impressions of a leaf with a radiating structure, and of part of a root, are perhaps remains of members of the Nymphiasae, but the evidence is not good enough to allow more than speculations.

The cast of a small lamellibranch was found preserved in black shale half-way between the above locality and Reinhardpynten: this however was unidentifiable.

The rocks have thus still to be precisely dated.

STRUCTURE.

The beds are not folded, but gentle warping has induced variations in the amount of dip between 30° and 50° to the east. More violent disturbances are seen in the neighbourhood of faults, where the rocks are locally twisted into a vertical attitude.

The major fault lines of the Tertiary are indicated on the geological maps A to C, and their attitude and relative displacements - where known - are indicated on the sections - A2 to C13. In the far north, the fault is single and vertical, but it dips east at about 70°, at the east of Balfourfjellet. Its attitude cannot be discovered again until Buchananryggen is reached, where three nearly vertical faults are seen. Here, the effect of a fault throwing down to the west has been to isolate a wedge of Hecla Hoek rocks from the main outcrop.— The Tertiary rocks are downfaulted on both sides of this wedge.

Further south, the fault system becomes more complex - six major faults cutting across the ridge of Sesshogda, north of Selvagen. Two of these dip to the east at little more than 60°, but the others are nearly vertical (section C6). Here again a wedge of Hecla Hoek rocks lies within the Tertiary belt and several other such wedges would appear if erosion proceeded a little further, for not all the faults throw down to the east. This fact is interpreted, as

resulting from variations in the amount of fall of each block within the graben system; that is, the apparent reverse faults are not considered to result from compression, but from differences in the relative downthrow of various wedges. There is no reason to interpret the graben system as anything but tensional.

The tear fault of Scotiadalen has already been discussed, and shewn to have a sinistral displacement, probably of about two and a half miles. Only one fault is seen south of Selvagen, but the complex system presumably persists, more easterly faults being hidden below the raised beaches, or lying east of Dawespynten.

Effects of the Graben faulting on the Tertiary rocks.

The effect of Tertiary movements upon the Hecla Hoek rocks, has already been described in Chapter III, (p. III). It only remains to mention the effects within the Tertiary rocks themselves. The general dip towards the centre of the graben has already been mentioned. In addition, in the far north the beds are twisted into an almost vertical attitude, parallel to the fault, for at least 1200ft. from it. This large scale dragging effect does not persist, however, for the beds east of Balfourfjellet, against the fault, dip at only 38°; and no similar phenomenon is met with further south - presumably because there the total downthrow is divided between several faults.

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