The Hecla Hoek ridge of the Devonian Graben between Liefdefjorden and Holtedahlfonna, Spitsbergen

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Contents

Geological setting

The ridge to be discussed in this paper, is located in the west part of the main Graben, between the two westernmost N–S trending faults on Orvin's 1940 map. It is bordered to the west by the NW Spitsbergen Hecla Hoek block, but a large glacier system — the Isachsenfonna and its northern continuation, Monacobreen — covers the border zone in a width of several kilometres all the way between Holtedahlfonna and Liefdefjorden. To the east follows the major Devonian system of Spitsbergen, preserved in the deepest part of the Graben.

Field work

In the early part of the geological exploration of Svalbard, during the 19th century, only the coastal region was investigated; most of the interior was geologically speaking unknown land. In 1911 Olaf Holtedahl made the first geological traverse of the area, pulling sledges from Krossfjorden to Woodfjorden, and from there to Ekmanfjorden. Unfortunately, the weather was most adverse, and he was not able to observe very much. Nevertheless, he noted the inland continuation of the Hecla Hoek system from Kongsfjorden and the existence of Red Bay conglomerate and marble in the highest part of the plateau (HOLTEDAHL 1914, 1926). During the English-Norwegian-Swedish Expedition 1939, mostly Devonian formations were studied, and investigation was made around the major fault zone at Vonbreen at the head of Woodfjorden (FØYN and HEINTZ 1943). JOHN PRESTON in 1957 explored the southern part of the ridge, from Holtedahlfonna to Eidsvollfjellet, and produced a geological map (1959). From 1959 to 1964 members of the Cambridge University Spitsbergen Expedition, headed by W. B. HARLAND, worked in the northern part of the ridge. Most of the work, by D. G. GEE, took place to the north of Liefdefjorden, and only preliminary reconnaissance studies near the coasts were carried out to the south. Some information on their work is given by GEE and MOODY-STUART (1966).

Members of the Svalbard expeditions of the Arctic Geology Institute of Leningrad (now SEVMORGEO) have worked in the area since 1962. Some accounts of their work on the volcanic rocks and the Devonian ones have been published (BUROV 1965; BUROV and MURASOV 1967), but no details of their studies of the Hecla Hoek stratigraphy, lithology, and structure have been known to me.

During some weeks of the summer seasons 1962–64, and on a snowscooter expedition in the spring of 1967, then accompanied by T. S. WINSNES, I was able to cover in a preliminary way most of the grounds of the ridge. My administrative duties, however, have, until recently, prevented me from microscopic and other laboratory studies of my samples. Therefore, only a general outline of the geology of the ridge will be presented here, and I shall only treat the Hecla Hoek sequence and the contact relationship to the Devonian rocks.

Lithology of the Hecla Hoek rocks

The following rock types, in various stages of metamorphism, are present:

1. Granite, migmatite, and gneiss.
2. Pelitic rocks, ranging from phyllite (greenschist facies), micaschist, and transition rocks to gneiss. Proper quartzite is rare, and occurs mainly in thin, inconsistent beds in the metasediments or as relics (paleosomes) in the granitic rocks.
3. Carbonate rocks, mostly pure calcite marble, sometimes also interbedded dolomite. In most cases banded or bedded types are found, the thickness of individual layers ranging from 1 mm to a few dm. In some areas massive, dense, or fine-grained marbles are found, in other areas coarse- to medium-grained ones. Fossils have nowhere been detected, neither have proper algal structures been observed, so far.

The maximum thickness of exposed strata in the ridge is in no place more than approximately 800 m, of which gneiss and/or pelitic strata make up 500 m. If my structural and stratigraphic considerations are correct, the total thickness of the exposed sequence in the investigated area may not exceed one kilometre.

Fig. 1. ⋙→

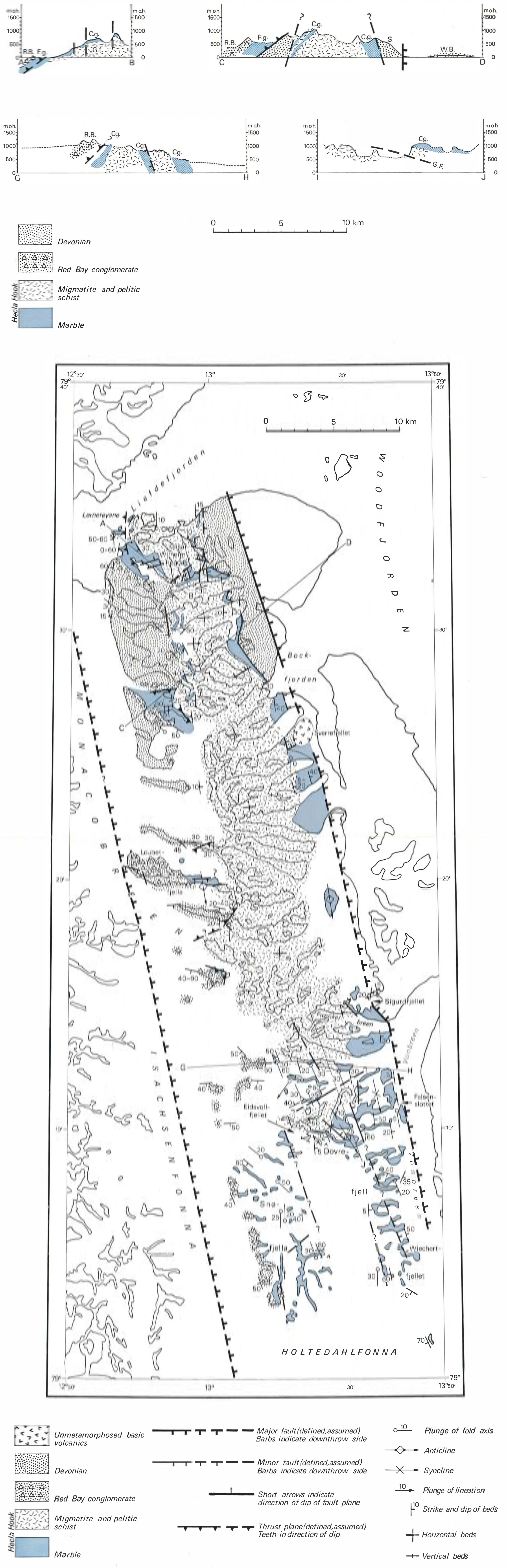

Fig. 1. *Geologic map and profiles: R.B. = Red Bay group. S = Siktefjellet group W.B. = Wood Bay group. C.g = coarse-grained. F.g = fine-grained.*

Distribution, stratigraphy, and petrology of rocks

Gneiss and migmatite occupy a broad, central part of the ridge from Fortunafjellet (a little to the north of Eidsvollfjellet-Falsenslottet) and northwards to Keisar Wilhelmhøgda, just south of Liefdefjorden (map, Fig. 1). The granitic rocks are very similar to the "grey granite", or migmatite, which is found in the NW corner of Spitsbergen (and to the west of Monacobreen), consisting of plagioclase (oligoclase), quartz, and micas. Plagioclase occurs also as scattered, rectangular porphyroblasts. Dark schlieren of biotite-ghosts or partly digested inclusions of pelitic rocks are ubiquitous. Angular and often rotated relics of schists and impure quartzite are commonly observed (Fig. 2). These features are all typical for the "grey granite" and migmatites in NW Spitsbergen. In various places gneisses containing a fair amount of FeMgCa silicates, such as hornblende, diopside, garnet, and even olivine, are found, partly near the contact of marble layers, but also elsewhere. In other localities sillimanite-bearing gneiss is observed. In one or two samples, cordierite or its alteration products are seen. These mineral assemblages indicate that the metamorphic grade during regional metamorphism and metasomatism reached upper amphibolite facies. Retrograde mineralization has taken place in zones of strong tectonization, such as thrustplanes. Here the highgrade minerals, along with plagioclase, have been altered to hydroxyl-bearing minerals: serpentine, antigorite, micas, chlorite, epidote, etc.

On the northern slope of the Keisar Wilhelmhøgda towards Liefdefjorden, coarse-grained, somewhat gneissified schists with dikes of granite are found in

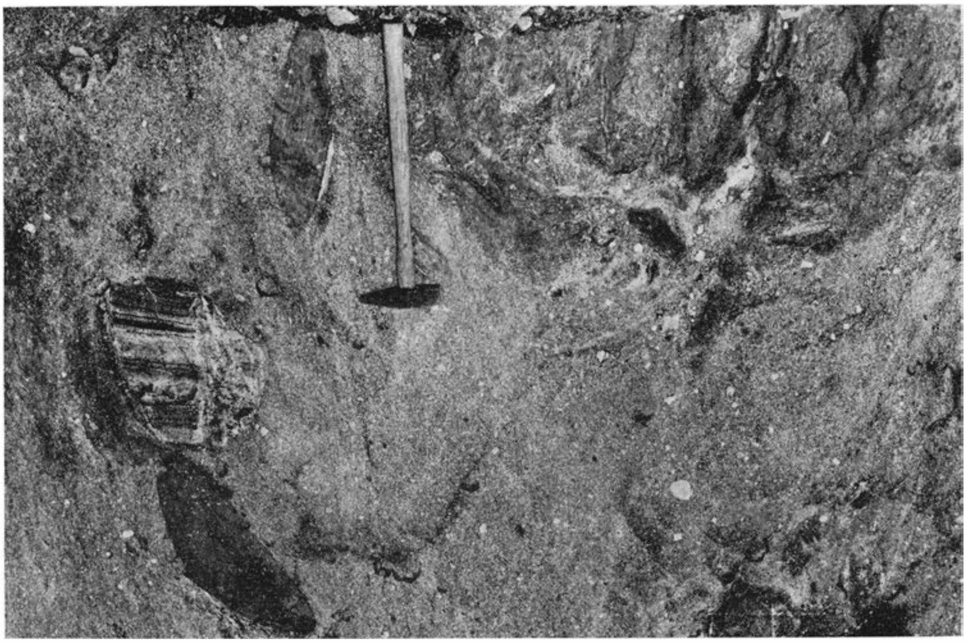

Fig. 2. *Migmatite from the Bockfjorden area. Note variety and relationship of fragments, indicating rotation, feldspar porphyroblasts and biotite-rich schlieren in the matrix.*

the lower part of the succession. Higher up they grade into schists of lower metamorphic facies, without taking on the greenish colour typical of the low-grade schists on the north side of Liefdefjorden. The metasediments on Lernerøyane in the fiord are in a transition stage of schist and gneiss, and contain minerals of amphibolite facies. A few thin beds of coarse-grained marble and numerous schlieren of sulphide-bearing reaction skarn lenses are intercalated.

In the northern half of the ridge, marble layers of two types are found. On the east flank, a minimum of 200 m thick, coarse- to medium-grained (·3–2 mm) marble layers are capping the gneiss zone, sometimes with a thin transition zone of micaschist or reaction skarn rocks. In the Keisar Wilhelmhøgda this marble layer is seen to bend over the gneiss, and is also found, mostly in thinner layers, at places along the west flank. Northwards from here, the coarse-grained marble layer, stepwise faulted down, can be followed rather continuously to the western Lernerøyane. On the east flank north of Keisar Wilhelmhøgda the coarse-grained marble cannot be traced continuously, but it outcrops again near the south shore of Liefdefjorden.

Impure beds of this marble formation contain the same minerals as those of the reaction skarn in the gneisses. Small lenses, often boudine-shaped, of dark green rocks occur, mostly consisting of diopside and hornblende with minor amounts of iron sulphides and trace amounts of other metal sulphide. In the gneiss, at some tens to one hundred metres, stratigraphically, below the main marble formation, small and rather discontinuous bands of the same marble are found.

The marble layer is not always fully concordant with the underlying gneiss. In most places the discordance is small and may be interpreted as a result of the difference in competence of the pelitic and carbonate beds during the orogeny. On the north side of Frænkelbreen (the northernmost tributary glacier of Vonbreen), a major discordance is located at the footwall of the marble layer. It is parallel to the adjacent main fault separating the ridge from the major Devonian Graben, and may thus be of post Hecla Hoek age.

The other type of marble, always fine-grained and mostly massive, is found only in the outer part of the west flank, an exception being some thin beds of dolomite and calcite marbles capping the central part of the northern slope of Keisar Wilhelmhøgda. When observable, the lower contact of the fine-grained marble is always a thrust zone, the underlying rock being either the coarse-grained marble or gneiss, in one place also Devonian rocks (Fig. 1, prof. C–D). Its upper contact always appears to be a weathered erosion surface, grading upwards into the typical Red Bay conglomerate. In these northern exposures, the fine-grained marble is a bluish grey, massive rock, frequently showing a criss-cross network of white veins, which mostly consists of calcite with subordinate quartz. In places, the marble contains thin beds of chlorite-muscovite schists.

The grain size of this marble formation ranges from submicroscopic to approximately ·1 mm. This feature, coupled with the mineral composition of the intercalated metapelites, indicates a metamorphic grade of greenschist facies.

Fig. 3. *Photo from NW: Falsenslottet (left), marble on top (white), biotite schist (black) below and in the forground. Eastern shoulder of Eidsvollfjellet (right) with the same beds. Fault located under the white talus on the left side of the saddle between the two mountains. The contorted structure of the marble beds behind the saddle are located in the south extension of the fault zone.*

In the southern part of the investigated area, comprising Eidsvollfjellet, Falsenslottet, and the two southwards running series of exposures, Snøfjella in the west and Dovrefjell-Wiechertfjellet in the east, only marble formations and pelitic schists make up the metamorphic sequence. The marbles consist of alternating calcite and dolomite beds of thicknesses ranging from a few mm to several tens of metres.

The rocks of Eidsvollfjellet-Falsenslottet mostly dip to the WSW and ENE due to folding with axis plunging to the SSE. Marbles occupy the higher parts, and are in the north wall underlain by black pelitic schists with scattered plagioclase porphyroblasts in some layers (Fig. 3). The marbles are medium- to coarse-grained, the schists are of high greenschist to low amphibolite facies. Despite the possibility of displacements by ENE running faults in between, the position of the Falsenslottet marble seems to match pretty well that of the eastern marble zone to the north.

In the axial part of Snøfjella, tightly folded, fine-grained marbles occur. They mostly dip to the WSW and are succeeded by typical Red Bay conglomerate with a transition zone of weathered marble and a sedimentation breccia of marble. In the northern part the strike bends to the NW because of SE dipping fold axes. A fairly thick bed of schists runs across the northernmost nunataks of Snøfjella in a SE direction. It is tightly folded and squeezed, but poorly exposed. Thus it is difficult to assess its real thickness. It contains some thin quartzite beds, and PRESTON (1959) reports also intercalations of quartz conglomerate. In two localities I have found highly altered, fine-grained feldspar-rich shale, which may be of either arkosic or volcanic origin.

In the Dovrefjell-Wiechertfjellet exposures, mostly beds of fine- to medium-grained marble are found, some of which contain a fair amount of graphite which emphasizes the banded character of the rocks. Thin bands of schists are occasionally found, exhibiting greenschist- to biotite-grade facies. Dips are mostly steeply to the east in the upper part of the slope, flattening eastwards and even dipping W near the Vonbreen glacier. In the westernmost (upper) part of some of the exposures, strongly folded beds are observed, with an axis dipping S or SSE.

Devonian rocks

The Devonian rocks of the east side of the Hecla Hoek antiform are rather uniform grey-green sandstones and some rare, black shales. FØYN and HEINTZ (1943) suggested that they belong to the Red Bay series, whereas GEE and MOODY-STUART (1966) point to the strong lithologic similarity to the Siktefjellet group north of Liefdefjorden (considered to be a formation older than the Red Bay group).

PRESTON (1959) reports the presence of Devonian rocks on some of the mountain tops in the Dovrefjell-Wiechertfjellet range. We did not find them, however. The pre-Devonian erosion (and weathering) surface was observed, and Devonian rocks may exist under some of the highest located snowcaps.

The Devonian on the west side of the Hecla Hoek rocks are definitely of Red Bay affinity, starting with a weathering surface of an in situ limestone breccia, upwards grading into more heterogeneous, but still limestone-dominated breccia or conglomerate of typical Red Bay facies. This again grades into a quartz pebble conglomerate. Upwards follow alternating beds of sandstones and thin beds of rounded pebble conglomerate, succeeded by alternating beds of sandstone and shale (correlatable with the Andréebreen and the Frænkelryggen members north of Liefdefjorden).

Young volcanic rocks

In Sverrefjellet, close to the main post-Devonian fault at the head of Bockfjorden, a core of fresh alkali basalt is found (HOEL et HOLTEDAHL 1911; GJELSVIK 1963). It is considered to be of post-glacial age (HOEL et HOLTEDAHL loc.cit.; BUROV 1965; SEMEVSKIJ 1965).

From Sigurdfjellet, north of Frænkelbreen, a similar rock is reported (HOEL et HOLTEDAHL loc.cit.). According to my recent observations, only pyroclastic rocks are present here, being deposited from a volcano, the neck of which is barely seen above the snow three kilometres to the west.

The top of the Eidsvollfjellet is capped by a rather flat-lying layer of unmetamorphic basalt, perhaps representing a flow. Mineralogically and structurally it is different from the Sverrefjellet basalt, and may be of Jurassic-Cretaceous or Tertiary age. A few dikes of it is found cutting the metamorphic rocks on the north slope of the mountain.

Tectonics

From the map and the profiles (Fig. 1) it is seen that the ridge is made up of a gentle antiform with NNW–SSE axis. Towards Liefdefjorden the antiform axis appears to plunge northwards. However, E–W faulting with downdrop to the N, has also taken place, and the plunge of the axis may not exceed 5–10^g.

In the southern part, the elevation of the mountains is somewhat higher and greater thicknesses of the capping marble formation have been left by the erosion. Also here faulting occurred. The marble formation as a whole forms gentle structures; internally, however, it is often tightly folded. Both in the marbles and in the pelitic schists, folds of various amplitudes, from micro-size to some 100 m, are observed. Most of the larger ones are gentle and open, and dip to the SSE. Many small folds, however, are isoclinal. Sometimes they dip in directions opposite to the larger ones. Systematic and detailed tectonical observations are not sufficient to allow a proper tectonical analysis, but it is my impression that the small folding is largely due to plastic flow in the rocks, and does not generally affect the Hecla Hoek ridge on a larger scale. One possible exception should be mentioned. A limestone bed of a few tens of metres exposed thickness just N of Eidsvollfjellet has been subjected to a most intense folding and stretching. Numerous small isoclinal folds, whose axial planes dip steeply to the SW are observed, with axis plunging between 15 to 60^g, averaging 30^g, to the SSE. The lineation of this limestone is unusually strong. The profile G–H cuts across this locality, as well as across another, somewhat faulted and also intensely folded limestone with the same general directions. It may be the other limb of a large, overturned anticline. The extensive ice cover, as well as the complicated fault pattern, makes it difficult to ascertain this hypothesis.

Beside the two major faults which delimit the ridge, a number of smaller NS faults are observed, most of them located in the eastern border area (Fig. 3). Also faults in EW and other directions are observed, particularly in the areas just N of Eidsvollfjellet and near Liefdefjorden. In my opinion, EW faulting is a major element in the formation of this fiord. Some of them also intersect Devonian formations.

Preston (1959) indicates a NNW–SSE fault between Snøfjella and Dovrefjell with downdrop to the east. Unfortunately, the area is completely covered by a big glacier. However, some tectonically disturbed marble beds in the nearest nunataks suggest movement along a NNW–SSE zone halfway between Snøfjella and Dovrefjell. Similar features are observed at the saddle between Eidsvollfjellet and Falsenslottet (Fig. 3), following the same direction southwards. It is possible that some kind of a faulted flexure is located here.

In the western half of the ridge a system of reverse faults exists, which represents some kind of imbrication thrusting involving both the Hecla Hoek and the Red Bay formations. The profile C–D (Fig. 1) is most instructive to demonstrate this. Some of the thrust zones indicated on the map are inferred from abnormal structural trends and the occurrence of the basal Red Bay conglomerate in relation to them. The tectonic transport during imbrication seems to have been towards NNE. The eastern border of this western thrust system, which is mostly covered by glaciers, is interpreted by me as part of the thrust system, since in most places where it is exposed, the contact is highly sheared and dips gently to the W.However, in the N, at Keisar Wilhelmhøgda, a steeply dipping shear zone (80^{g}E) indicates more vertical movements. GEE and MOODY-STUART (1966) report that the Devonian formations in the eastern part of the ridge between Bockfjorden and Liefdefjorden in part are faulted, in part thrusted against the Hecla Hoek rocks. Due to the extensive talus which covers the contacts, particularly those of the outlayers north of Børrebreen, I have not been able to verify this. The dip of the lower contact of the eastern Devonian formation is only about 10^{g} steeper than that of the underlying marble formation (see Fig. 5 of GEE and MOODY-STUART (loc.cit.)).

Discussion

The outlined tectonic relationship within the ridge raises two interesting questions. The first one is of stratigraphical importance: are the two limestone formations which are so sharply contrasted in the northern half, two different formations? Or is the difference due only to the tectonic and metamorphic history? For a while I was inclined to believe in the first alternative, but a study of the metamorphic grade of the pelitic sediments, and of the grain size of the marbles in the southern part of the ridge, have brought me nearer to the second alternative. As mentioned above, there seems to be a gradual change southwards in metamorphic facies as well as in grain size and the difference in both respects between the eastern and western area to the south of Eidsvollfjellet is small indeed. Furthermore, the imbrication thrusts cannot be established south of the E–W faults on the north side of Eidsvollfjellet.

The other problem concerns the time of the formation of the antiform structure. Some faults and thrusts affect also the Devonian formation present, and must therefore be of Svalbardian or later age. The trend of the antiform, as well as most other folds, are the same as in the major Hecla Hoek block to the W. By interference it would mean a Caledonian time of folding. However, as seen from the northern profiles (Fig. 1), the doming may have involved also the outliers of Devonian (Siktefjellet group). In the southern part, the pre-Devonian peneplain also dips in conformance with the antiform pattern: to the W in the western part, and to the E in the eastern part. This could mean that the antiform structure is of a later age than the main Caledonian fold periods. The Soviet K/A age determination of two samples of the grey gneiss in the Bockfjorden area (KRASIL'ŠČIKOV et al. 1964) gave 385 million years for both samples. If this is the true age of the granite intrusion, or the granitization process, the antiform could have been formed by this process after the deposition of the basal Devonian formations. If this is so, one would have expected that granite veins should have penetrated the Devonian somewhere. So far, it has not been observed. Alternatively, the antiform structure could have been formed by a central uplift, longitudinal faulting and tilting systematically to the E and W. The structures in the southern part may fit this alternative, in the north they seem better explained by folding. A more detailed tectonic analysis, as well as more and better geochronologic data, are needed to clarify this question.

As to the stratigraphical correlation of the Hecla Hoek rocks of the ridge, the thin slice of the stratigraphic column which is exposed, approximately 1,000 m, and the lack of fossiliferous or other marker beds make it possible only to give a rough guess. The similarity of the fine-grained limestone formation in Snøfjella and northwards to Liefdefjorden, and the marble formation of Blomstrandhalvøya in Kongsfjorden, makes it reasonable to suggest that the rocks exposed in the ridge belong to the Generalfjella Formation (GEE and HJELLE 1966). If it should include also the underlying Signehamna and Nissenfjella Formations, it would mean a most radical thinning to the east of these formations.

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References

BUROV, JU. P., 1965: Peridotite inclusions and bombs in the trachybasalts of Sverre volcano in Vestspitsbergen. *Mat-ly po geol. Spicbergena.* NIIGA, Leningrad. In English translation: Geology of Spitsbergen, 1965. National Lending Library for Science and Technology. Boston Spa, Yorkshire, England, 1970.

BUROV, JU. P. and L. G. MURAŠOV, 1967: Some results of a lithostratigraphic study of the Kapp Kjeldsen Formation in the region of Bockfjorden (in Russian). *Mat-ly po strat. Spicbergena.* NIIGA, Leningrad.

FÖYN, SVEN and ANATOL HEINTZ, 1943: The Downtonian and Devonian Vertebrates of Spitsbergen. VIII. *Norges Svalbard- og Ishavs-undersøkelser Skrifter* Nr. 85.

GEE, DAVID G. and AUDUN HJELLE, 1966: On the crystalline rocks of north-west Spitsbergen. *Norsk Polarinstitutt Årbok* 1964: 31–45.

GEE, DAVID G. and MARK MOODY-STUART, 1966: The base of the Old Red Sandstone in central north Haakon VII Land, Spitsbergen. *Norsk Polarinstitutt Årbok* 1964: 57–68.

GJELSVIK, TORE, 1963: Remarks on the structure and composition of the Sverrefjellet volcano, Bockfjorden, Vestspitsbergen. *Norsk Polarinstitutt Årbok* 1962: 50–54.

HOEL, A. and O. HOLTEDAHL, 1911: Les nappes de lave, les volcans et les sources thermales dans les environs de la baie Wood au Spitsberg. *Vid. Selsk. Skrifter. I. Mat.-Naturv. Kl. no. 8.*

HOLTEDAHL, O., 1914: New features in the geology of northwestern Spitsbergen. *Amer. Journ. of Science* **37**.

— 1926: Notes on the geology of northwestern Spitsbergen. *Norges Svalbard- og Ishavs-undersøkelser Skrifter* Nr. 8.

KRASIL'ŠČIKOV, A. A. et al., 1964: On the age of some granitoid rocks and gneisses of the northern part of the archipelago of Spitsbergen (in Russian). *Dokl. AN SSSR* **159** (4).

PRESTON, JOHN, 1959: The geology of the Snøfjella and Dovrefjella in Vestspitsbergen. *Geol. Mag.* **XCVI** (1).

SEMEVSKIJ, D. V., 1965: Age of the Sverre Volcano. *Mat-ly po geol. Spicbergena.* NIIGA, Leningrad. In English translation: Geology of Spitsbergen, 1965. National Lending Library for Science and Technology. Boston Spa, Yorkshire, England, 1970.