Peculiar features of regional metamorphism of northwestern Spitsbergen

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Abstract

Main features of geology and metamorphism of northwestern Svalbard are presented in the paper. On the basis of a lithological analysis, a division into formations of the metamorphic successions of the Precambrian is produced. The crystalline complex of the base of the Caledonides and the main geosynclinal complex have been recognized. The main regular patterns and succession of the metamorphic transformations have been exposed. A petrographic study and an analysis of paragenetic associations have made possible a conclusion on the superposition of the Caledonian metamorphism on to the crystalline rocks of the basement. The latter circumstance has predetermined a vast development of processes of ultrametamorphism in Caledonian time.

Introduction

For several years the author has carried out geologic-petrographic studies of metamorphic rocks in north-western Spitsbergen. The study area is bounded to the south by Kongsfjorden and to the east by a major fault extending southward from Raudfjorden along Monacobreen and Isachsenfonna. The area includes Amsterdamøya and Danskøya. The author was a member of the Spitsbergen Expedition of the Research Institute of the Geology of the Arctic. Study of mineral composition and the metamorphic history of the area were the main aims of the investigation.

Previous work

North-western Spitsbergen has attracted the attention of geologists from different countries since the second half of the last century; works by HOEL, HOLTEDAL, SCHENK, FREBOLD and HARLAND are well known. The results of earlier investigations are reviewed in recent papers by GEE and HJELLE (1966), HJELLE and OHTA (1974) and KRASIL'ŠČIKOV (1973).

GEE and HJELLE (1966) proposed a stratigraphic standard section for slightly metamorphosed Upper Proterozoic rocks in the Krossfjorden area. They recognized a migmatite complex at the base of the section, overlain by three rock units totalling a thickness of 7000–7500 m.

The Nissenfjella Formation was reported from the western coast in the Nissenfjella area. It is composed of "pelites" with numerous thin amphibolite lenses and bands. The lower part of the formation contains granitized rocks which increase in quantity northward. The upper boundary is drawn at the disappearance of amphibolites.

The Signehamna Formation outcrops in Mitrahalvøya and on the shores of Krossfjorden. It is represented by a homogenoeus "pelites" with subordinate "psammites" and quartzites.

The Generalfjella Formation caps the sequence of metamorphic rocks in the area and is composed mainly of marbles and quartzites.

Later HJELLE (in: HJELLE and OHTA 1974) rejected the previously recognized Nissenfjella Formation and considered the whole complex of deeply metamorphosed rocks to be equivalent to the Signehamna and Generalfjella Formations, granitized and migmatized during the Caledonian orogeny.

KRASIL'ŠČIKOV (1973) in his papers on the tectonic reconstruction of the archipelago in the pre-Cambrian–Lower Paleozoic, recognizes a crystalline basement of the Caledonides (presumably of Lower-Middle Proterozoic age) and a major geosynclinal complex composed of Upper Proterozoic rocks. Thus, at present there are two opposing concepts of north-western Spitsbergen geology.

Geological setting

The analysis of previous investigations and the evidence obtained by the author allow a new interpretation of the main features of north-western Spitsbergen geology.

A granite-gneiss complex, made up of both granitized and migmatized Riphean rocks and relics of deeply metamorphozed Caledonide basement, lies at the base of the metamorphic rock section. Because of the present lack of knowledge it is impossible to map separately formations within this complex.

The granitized Riphean rocks are represented at the base by the Nissenfjella Formation, overlain by the Signehamna and Generalfjella Formations.

Igneous rocks consist of the Pre-Riphean dyke complex of basic rocks and Caledonian granitoids, among which synorogenic and post-orogenic intrusions may be distinguished.

It has been suggested that a southward plunge of fold axes, one of the main structural features of the region, accounts for the exposure of deeper parts of the section in the northern areas. In my opinion block tectonics resulted in the juxtaposition of rocks of different metamorphic grade, and are of great importance.

Stratigraphy

The scheme proposed by GEE and HJELLE (1966) is used as a basis for stratigraphic subdivision. However, while sedimentary layering of the slightly metamorphosed upper subdivisions (the Signehamna and Generalfjella Formations) is evident, the mapping of the underlying Nissenfjella Formation presents some difficulties. This is because the metamorphic facies boundary does not coincide with and thereby obscures the stratigraphic boundaries. A stratigraphic succession in the area follows:

A — Pre-Riphean complex, the basement of Caledonian geosyncline

B — Riphean geosynclinal complex:

1 — Nissenfjella Formation

2 — Signehamna Formation

3 — Generalfjella Formation

Geologic and petrographic characteristics are given below for each stratigraphic unit.

PRE-RIPHEAN COMPLEX, THE BASEMENT OF CALEDONIAN GEOSYNCLINE

This is largely a granite-gneiss complex underlying more than half of the study area. To the south, in the Conwaybreen area, it consists of a N–S trending band 4 km wide gradually widening northward. In the Kollerbreen area this band is 10–11 km wide and in the Magdalenefjorden–Raudfjorden area and farther north the granitegneiss complex reaches 20–27 km in width. It extends for more than 100 km from south to north.

This complex consists largely of biotite, biotite-garnet, biotite-amphibole, and biotite-cordierite in places with sillimanite gneisses and plagiogneisses. Thin bands of skarns occur throughout the section. Amphibolite lenses and bands occur in the western part of the complex (Danskøya, Amsterdamøya and southern coast of Bjørnefjorden).

Magnesian and aluminous rocks may be distinguished by their different bulk chemical compositions. Magnesian rocks occur in Danskøya and Amsterdamøya and on the peninsula between Bjørnefjorden and Magdalenefjorden. Aluminous rocks occur in the eastern exposures of the granite-gneiss complex.

Biotite gneisses, biotite-amphibolite, clinopyroxene-amphibolite, and biotite-garnet gneisses and plagiogneisses dominate in the magnesian-rich parts. Bands of carbonate rocks are represented by salitic pyroxene and marbles with diopside, scapolite, garnet, and wollastonite assemblages. Feldspar amphibolites, concordant with the surrounding rocks, occur as thin lenticular beds. Highly aluminous rocks such as biotite-cordierite gneisses and plagiogneisses are not characteristic of this complex. They occur as scarce, thin beds pinching out along strike.

In the eastern part of the granite-gneiss complex, biotite-cordierite gneisses and occasionally plagiogneisses with low sillimanite content predominate, with biotite gneisses and plagiogneisses. Biotite-garnet gneisses occur in the form of thin lenticular beds. Diopside, olivine, wollastonite, prehnite, muscovite, with spinel, gummite and phlogopite are the most common minerals in the marble. Amphibolite bodies, and beds containing scapolite and amphibole gneiss units are absent in this part.

The base of the sequence is unknown. This contact with overlying succession in many places is a tectonic one. In particular this is true of the eastern contact. To the south in the Conwaybreen area the boundary follows a glacier, and granitoids are cataclastic in the contact zone. The western contact of the granite-gneiss has a complex pattern. Lines of granite intrusions occur along the contact zone, and cataclastics are common. This extensive zone of cataclasis can be traced along the eastern coast of Smeerenburgfjorden. Farther south a big intrusion of the Hornemantoppen granite is related to this zone. In the Kollerfjorden, Mayerbreen, and Tinayrebreen areas there are small intrusions of synorogenic granites probably also related to this tectonically weakened zone. There is no evident unconformity and a transitional zone up to 100 m thick impregnated with granitoid material lies adjacent to the contact.

In Amsterdamøya, Danskøya and Hoelhalvøya, granitized and migmatized rocks of the Nissenfjella Formation cannot be distinguished from the Pre-Riphean complex.

RIPHEAN GEOSYNCLINAL COMPLEX

The Nissenfjella Formation lies at the base of an up to 3 km wide outcrop of the Riphean complex. It consists mainly of biotite plagiogneisses with porphyroblastic texture and banded gneisses. There are occasional lenses of feldspar amphibolite. A characteristic feature is the complete absence of highly aluminous rocks. The amount of granite gradually increases from south to north, and on Hoelhalvøya layered migmatites are present. The Nissenfjella Formation can be recognized in the south-western Danskøya. The contact with the overlying Signehamna Formation on the west coast of Spitsbergen follows a thrust of N–S trend and eastward dip.

The Signehamna Formation occurs on the shores of Krossfjorden where it forms the limbs of a complex synclinal structure. In southern Mitrahalvøya the formation is composed of mica-quartz-albite slates, and in the northern part of mica-quartz-garnet-albite slates. In Kong Haakons Halvøy and Kapp Guissez, quartzite beds are intercalated with the slates. The outcrop on the northern coast of Kongsfjorden consists of mica-quartz-albite slates. There is a stratigraphic contact with the overlying Generalfjella Formation.

The Generalfjella Formation is exposed in central Mitrahalvøya where it forms the core of a syncline. It also outcrops as a northward narrowing band from Blomstrandhalvøya in the south, to Tinayrebreen in the north. Another small outcrop forms a N–S trending band at the mouth of Conwaybreen pinching out at Fjortende Julibreen. The formation consists of marbles of varying colours.

PETROGRAPHY. METAMORPHISM, AND ULTRAMETAMORPHISM

Marbles making up the Generalfjella Formation are inequigranular and fully recrystalline. Their composition is close to that of limestones with a significant magnesium content. The content of dolomite ranges from 5 to 25 per cent. Thermal studies of the marbles gave a temperature of carbon combustion of 550°, corresponding to greenschist facies metamorphic conditions (BLJUMAN et al. 1974).

There are two dominant rock types in the Signehamna Formation, mica-albite-quartz and mica-oligoclase-quartz-garnet slates. Numerous determination of refractive indices and orientation of optical indicatrix showed that the former contain only albite (An_{10}) while the latter include acid oligolcases (An_{9-14}). The garnet is close in composition to almandine (83%). Tourmaline is a notable accessory mineral. The mica-albite-quartz association corresponds to the greenschist facies recognized by ESKOLA. Albite-epidote-chlorite is considered to be a diagnostic association of the greenschist facies. However, TURNER (1951) points out that an abrupt change in plagioclase composition from albite (An_{0-7}) to oligoclase (An_{15-20}) takes place with increase in metamorphic grade of pelites to the almandine zone. This change in plagioclase composition marks the high temperature limit of the greenschist facies. SUDOVIKOV (1964) claims that with the appropriate K content and relatively high temperatures, chlorite may be completely replaced by biotite, and calcic epidote by muscovite.

Another characteristic association, oligoclase-almandine-biotite, corresponds to the epidote-amphibolite facies (SUDOVIKOV 1964). Thus, mica-albite-quartz is characteristic of high temperature subfacies of the greenschist facies and of a zone transitional to epidote-amphibolite facies. This reflects the increase in grade of metamorphism with depth. The mica-olig-Qz-garnet association is characteristic of a higher grade of metamorphism marked by the appearance of garnet in the epidote-amphibolite facies.

The Nissenfjella rocks are also characterized by anolig oclase, biotite-garnet paragenesis. Almandine is the predominant component of garnet (53–69%) but the grossularite content (21–36%) is significant. Biotite pleochroic from dark brown with a greenish tint to colourless grey, with a molecular Fe content from 40 to 50%, is common. This mineral association also corresponds to the epidote-amphibolite facies. Thus, the rocks composing the lower part of the Riphean geosynclinal complex formed under the conditions of greenschist and epidote-amphibolite facies metamorphism. A gradual increase in metamorphic grade occurs through the section and the boundary between the two facies is the Signehamna Formation.

Gneisses and plagiogneisses building up the Pre-Riphean granite-gneiss complex have a distinct granoblastic texture and gneissic or flow-structure. Usually they are equigranular and homogeneous with an average grain size of

1.5 to 2.0 mm. In eutaxitic varieties minerals are differentially distributed in the form of quartz-feldspar bands and bands enriched with mafic minerals.

Plagioclase is represented by two minerals. Acid-intermediate andesite (An_{20-40}) is most common. Labradorite (An_{50-70}) is less common and occurs mainly in Amsterdamøya and Danskøya and in northern Albert I Land. Potash feldspar occurs in the form of orthoclase-anorthoclase. Amphiboles are usually represented by hornblende with a molecular Fe content of 27 to 65%. Cumming tonite is less common. Biotite in the rocks free from granitization is duller in colour with a molccular Fe content of 40 to 50%. Cordierite occurs as both fresh unaltered grains, and partly or completely converted into pinite. Molecular Fe content of the cordierite is usually 18 to 20%. Garnet is usually unaltered euhedra with rare intensely chloritized varieties. Almandine (58–72%) predominates, the pyrope content slightly higher (17–25%) compared to the Riphean rocks.

Paragenetic associations of the above listed minerals are stable only under the conditions of the amphibolite facies. Specific conditions due to partial melting commencing at this stage effect mineral assemblages. Taking this into account, SUDOVIKOV (1964) divided the amphibolite facies into two subfacies; relatively low temperature staurolite-kyanite and higher temperature sillimanite-almandine. Rocks not affected by ultra-metamorphism belong to the former, and those which have undergone melting, to the latter.

An important feature of regional metamorphism in north-western Spitsbergen is that the transition to rocks of the granite-gneiss complex is accompanied by an abrupt increase in metamorphic grade.

A remarkable feature of the region is an exposure of the Caledonian ultrametamorphism zone, an area of early melting and magma generation with inclusions of unmelted substratum. The volume of the melt accounts for the injection and movement of the bulk of the rock. Migmatite formation, granitization, and anatexis were widely operative.

Bearing in mind the different usage of the above terms by many geologists it is appropriate to explain their meaning as they are used in the present paper. According to READ (1949) granitization is the transformation of solid metamorphic rocks into granitic rocks without passing the magmatic stage. The refinement proposed by NIGGLI (1949) that granitization incorporates recrystallization accompanied by pneumatolytic-hydrothermal processes is also appropriate in this case. The term "anatexis" is taken to mean granitization accompanied by melting.

The most homogeneous parts of the melting zones could have been injected into higher beds during partial melting.

Migmatites of different morphological types are widespread. White, light-grey granitoids occur as vein material. The paleozones consist of plagiogneiss and gneiss of the Pre-Riphean complex. Lenticular bodies, up to 0.8–1.0 m, of pegmatitic granitoid often occur in the vein material. Thus, the melt which gradually developed in the zone of ultrametamorphism, is thought to have been injected in the form of vein material.

There is a gradation between migmatites of different types. They are all related by a granite migmatite vein material. The process of granitization accounts for the appearance of closely related granite migmatites. Migmatization took place simultaneously or before granitization, resulting in the formation of layered migmatites. During their formation granite migmatites were in a plastic state and were able to move over short distances. This is shown by the numerous xenoliths and skialiths of plagiomigmatites, plagiogneisses and gneisses in the matrix. Granite migmatites forming at a centre (perhaps a central part of a partial melting chamber) were withdrawn from migmatites, skialiths and similar relics in the matrix. They became lighter and more homogeneous and the gneissic structure disappeared. This occurred when the bulk of the rock melted and could be injected. Synorogenic anatectic granites formed on solidification. The presence of garnet, sillimanite and cordierite, minerals not characteristic of normal igneous rocks, provides support for this view.

Local processes of sodium and solicic-potash metasomatism were operative during the final stage. In general porphyroblasts were not oriented, indicating their formation subsequent to the main stage of deformation.

The petrographic study of the granitoids indicates zonal features and an effect on rocks of the Pre-Riphean basement. In all the granitoids, plagioclase has an extremely, constant composition of basic oligoclase (An_{25-30}). Potash feldspar is usually represented by orthoclase-anorthoclase and, only in granites of Miethebreen, by lattice-twinned microcline. A characteristic feature is the predominance of plagioclase over potash feldspar. Only rocks subjected to silicic-potassium metasomatism, is the composition close to that of typical granites. Newly formed biotite is bright redbrown in colour and its molecular Fe content ranges up to 60–65%. Another feature characteristic of most of the granitoids is the presence of two generations of plagioclase, potash feldspar, and biotite. The combination of successive stages of plagioclase formation resulted in the coexistence of plagioclases with different anorthite content in a given rock. The geological study of migmatites and granite migmatites and their relationships suggest at least two stages of migmatization and granitization. The Caledonian metamorphism effected the earlier migmatized and granitized rocks. The formation of the latter took place under the conditions of at least amphibolite facies.

The highest grade of metamorphism in Caledonian time appears to be reflected by ultrametamorphism characterized by the formation of plagioclase with a composition not higher than that of oligoclase-acid andesite. It follows that the presence in plagiogneisses of a plagioclase matrix with a composition of basic andesite and even labradorite argues for Pre-Caledonian conditions of metamorphism higher than those of the Caledonian metamorphism.

Conclusions

The area includes two main rock-units, the Pre-Riphean basement and the Riphean geosynclinal complex.

Two units differing in lithology of enclosing rocks are recognized in the Pre-Riphean basement.

The Riphean complex is mapped as a single syncline closing in central Lilliehöökbreen.

The basement complex is polymetamorphic in origin. Metamorphic events of Pre-Caledonian time predated the widespread processes of ultrametamorphism in Caledonian time. Petrographic studies show the spuerposition of low temperature associations of amphibolite facies on high temperature Pre-Caledonian facies.

Two stages of migmatization — Pre-Caledonian and Caledonian — have been recognized.

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