Is there an early Precambrian granite-gneiss complex in northwestern Spitsbergen?

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Abstract

Rocks of near-contact zones of granitoid intrusions in northwestern Spitsbergen which by previous investigators of this region have been assigned to the gneiss-magmatic complexes of regional metamorphism of the early Precambrian, are described. In connection with a detailed study of these rocks it has come out that they are represented mainly by biotitic hornfelses and hornfelsified schists (with cordierite and sillimanite), having formed in the process of contact metamorphism from phyllites of the lower part of the Hecla Hoek Group. In this connection their affiliation to the granite-gneissose complex of early Precambrian age is made an object of doubt in the paper. The assumption is put forth that the rocks described are contactmeta-morphic, having formed in connection with an intrusion of Caledonian granitoids.

Introduction

Krasil'ščikov (1973) states: "... the pre-Riphean basement of the Caledonides outcrops in the northeast part of the archipelago, in western Ny Friesland, in southwestern (Hornsund) and in northwestern Spitsbergen. Early pre-Riphean formations are unknown in Svalbard. The oldest rock-type in the archipelago is probably granite-gneiss (of the deeply eroded outcrop of the basement) formed by the pre-Riphean ultrametamorphism of biotite and garnet-biotite paragneisses, relics of which are preserved as skialiths in granite bodies." (p. 84).

KRASIL'ŠČIKOV concluded this on the basis of traverses (scale 1:100,000) in the Krossfjorden area which had been carried out by ABAKUMOV in 1969 (ABAKUMOV 1976). He traversed the area bounded by 78°57′ and 79°20′ N, and 11°40′ and 12°20′ E, including exposures on the flanks of the Kollerbreen, Fjortende Julibreen, Conwaybreen, and Kronebreen, and on the shores of Krossfjorden and Kongsfjorden in north-western Spitsbergen.

ABAKUMOV described and mapped three formations at a scale of 1:100,000. The Signehamna and Generalfjella Formations, first described by GEE and HJELLE (1966), are of Riphean age (lower part of the Hecla Hoek). They consist of greenschist facies metamorphics with a total thickness of 8000 m and are common in Spitsbergen. The third formation, the Kollerbreen Formation, is at least 3500 m thick, and is assigned to the Lower-Middle Proterozoic (ABAKUMOV 1976). According to ABAKUMOV the Formation consists mainly of metasomatic migmatite and various gneisses (biotite, biotite-garnet, biotite-amphibole, biotite-sillimanite, biotite-cordierite, etc.). Numerous photographs and sketches show that the gneisses usually occur in metasomatic granite, sometimes as units 100–250 m thick, and contain skialiths and occasionally zenoliths. Massive granite (anatexite) is subordinate and occupies the central part of the Formation.

A narrow zone (2–4 km) of the Kollerbreen Formation trending approximately north–south, extends for more than 40 km in the eastern part of the area. This zone is associated with a fracture zone, and its contacts with other formations seem to be mainly tectonic though in places gradational contacts may be observed where other formations occur within the fracture zone.

In ABAKUMOV's opinion the Kollerbreen Formation formed under amphibolite facies regional metamorphism. The increase in metamorphic grade was accompanied by an increase in plagiofeldspathization and plagiomigmatization under the amphibolite facies conditions, followed by ultrametamorphism. This resulted in partial melting, the formation of bodies of heterogeneous plagiogranite, and then homogenous plagiogranite and anatexite. When the anatexites attained a certain critical state, they were intruded into higher levels. The second stage was the potassium metasomatism and granitization and was mainly associated with earlier melts.

The Svalbard archipelago is situated in an area of Caledonian folding which influenced later tectonism (KRASIL'ŠČIKOV 1973). Caledonian structures usually involve both the Riphean and older basement rocks. Because of the close association between Riphean greenschists and the older crystalline basement rocks, in situ observations are necessary for interpretation in the Kongsfjorden and Krossfjorden area. Dating may be misleading; for example absolute age determinations of the so-called Lower Proterozoic basement gneiss yielded 420–440 m.y., indicating that they formed during the Caledonian orogeny (KRASIL'ŠČIKOV 1973).

The author, who had been studying the crystalline basements of ancient platforms for twenty years, visited the Kollerbreen Formation exposures from a field camp on the Krossfjorden coast with ABAKUMOV in July 1972. Three sequences were studied across strike in the upper reaches of the Kollerbreen,

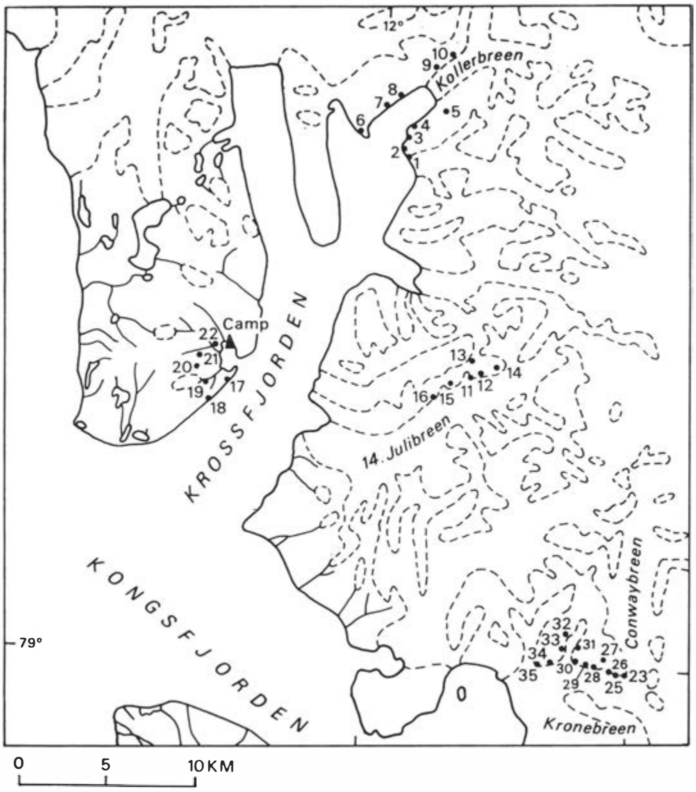

Fig. 1. *Map of the study area in northwestern Spitsbergen.*
•10*: Numbers of outcrops in* M. G. RAVICH's *routes in* 1972.

Fjortende Julibreen, and Kronebreen totalling about 25 km of outcrops of the Kollerbreen Formation. About 100 samples were collected. Petrographic and chemical study of these samples, as well as additional absolute age determinations, provided evidence for a new interpretation of the composition and origin of the Kollerbreen Formation.

In the field the "migmatites" and "gneisses" associated with granite bodies appear to be contact-metamorphosed, originating from the two-mica schists and phyllites of the Signehamna Formation. The so-called metasomatic granite and granite-gneiss that seem to predominate in the Kollerbreen Formation may have formed during injection of granitic melt; after crystallization the country rock shattered to a varying degree under stress resulting in poorly defined banding and quasi-gneissosity. Therefore the rock formerly called metasomatic granite and granite-gneiss is actually shattered plagiogranite and granite (granodiorite), while migmatite is actually schistose hornfels injected by aplitic and quartzose material. Gneiss is hornfels that retained the schistosity of the original phyllite and in places has a gneissose habit.

Along the glacier flanks there is a noticeable repeated alternation of granite bodies, concordant with contact metamorphosed phyllite, with units 150–

250 m thick of hornfels and quasi-migmatite. Discordant granitoid dome-like bodies (several hundred metres in size) were also observed. Contacts of the concordant granites and dome-like granitoid bodies with the contact metamorphosed phyllite are always sharp. But contacts of the two-mica schist and phyllite with the contact metamorphosed rock and quasi-migmatite (where the contacts have not been cut by faults) are always obscure and gradational.

The description of rocks of the Kollerbreen Formation will be given below.

Petrography

The following rock types occur in the area under study:

A. Country rocks

1. Two-mica schist with intercalations of chlorite-mica schist, quartzite and marble, making up the Signehamna Formation below.
2. Marble with intercalations of mica schist and quartzite constituting the Generalfjella Formation above.

B. Granitoids

3. Granite and plagiogranite approaching granodiorite.

C. Contact metamorphic rocks

4. Biotite hornfels and contact metamorphosed schist (in places with cordierite and sillimanite).
5. Contact calciphyre.

COUNTRY ROCKS

A two-mica schist is wide-spread throughout the area. Generally it appears rather uniform, though the percentages of the constituent minerals vary considerably: fine flaked muscovite — 15 to 50%, fine flaked biotite — 10 to 25%, quartz — 30 to 70%, and all the remaining minerals (almandine, spinel, plagioclase, tourmaline, hematite, sometimes apatite) — 3 to 6%. Although the latter form a minor component, they are very interesting and are of a quite different genesis.

The schist matrix consists of 0.03–0.1 mm slightly recrystalized quartz grains. These are interwoven into aggregates of light-brown biotite and colourless muscovite, which are strongly crimped and elongated along schistosity. The micas seem to have developed from the cement of the original siltstone. In the schist, up to 2–3% of fine fragments and skeletal grains of garnet (0.1 to 2.3 mm in size) are observed. Sometimes the garnets form piles of contiguous euhedral crystals as if cemented with biotite, and sericite flakes associating ore minerals. The garnet has an obvious clastic nature and is a typical terrigenous mineral bearing no relation to the paragenetic schist association. Much rarer rounded grains (0.1–0.2 mm) of green spinel occur in the same way. But bluish-greenish columnar crystals of tourmaline, up to 0.1–0.2 mm in length, scattered throughout the rock obviously have a neogenic habit, possibly due to neighbouring (at a distance of several hundred metres) granite bodies. Fine apatite crystals are minerals of the same category. The genesis of the fine (0.1–0.2 mm) isometric lathes of plagioclase, sometimes up to 2–3%, is not clear. From their crystalline forms they also appear to be neogenic.

In some schists chlorite is almost as abundant as biotite. Other schist varieties usually resemble laminated quartzite due to the small amount of mica. Finally the third schist group consists mainly of carbonate and mica flakes, while quartz grains constitute only 33% of the rock. All of the schist varieties are cut by quartz veins varying from thread-like to 5–10 cm thick. The number of quartz veins increases towards the granite bodies.

Marble and quartzite predominate in the upper part of the sequence of Riphean metasediments. Marble is characterized by wonderful homogeneity and fine-grained structure. It consists of equidimensional 0.1–0.2 mm isometric grains of calcite, often with cross-shaped polysynthetic twins. By contrast, quartzite is impure and generally contains 70–90″ of quartz, as well as albite (An_{5-6})[1], muscovite and biotite (5–10% in all) and rare calcite grains. Recrystallized and shattered quartz grains 0.05–0.1 mm in size of irregular shape, sometimes indented, make up the matrix. Irregular albite lathes are no more than 0.1–0.2 mm in size. Mica flakes, less than 0.05 mm in length, are uniformly scattered throughout the rock and do not form aggregates.

Rare schist intercalations in the quartzite differ from the typical two-mica schist described above. They contain far less quartz (no more than 30%), and micas make up more than half of the rock (up to 60%). Greenish-brown biotite flakes predominate over colourless muscovite flakes. Mica flakes reach 1 mm in length and they are mixed with chlorite, forming independent aggregates together with ore minerals.

In summary, the metasediments of the area are characterized by a simple association of minerals: quartz, albite, chlorite, muscovite and biotite, which are associated with the muscovite-chlorite and biotite-chlorite subfacies of greenschist facies of regional metamorphism.

GRANITOIDS

The metasedimentary rocks described above form the country rock around intruded granites associated with the narrow fracture zone crossing the whole area along its eastern edge.

In sections along the flanks of the three glaciers, heterogeneous granitoids, different for each glacier, are exposed. In exposures of Kollerbreen, plagiogranite similar to granodiorite in composition, is developed. It is practically devoid of orthoclase, and contains andesine, and relatively low percentages of quartz. In the rock along the Fjortende Julibreen, there are outcrops of leucocratic granite, with oligoclase and orthoclase present in almost equal quantities and biotite subordinate. And, last, in the Conwaybreen (Kronebreen) glacier rocks, granite is exposed with a predominance of oligoclase-andesine over orthoclase and with increased biotite content.

[1] Here and everywhere in the work the composition of plagioclase has been determined with the aid of the Fedorov universal stage.

Plagio-granite is usually represented by fresh medium to fine-grained slightly cataclastic rock. It has a hypidiomorphic granular texture, close to prismoid granular.

Zoned plagioclases are predominant (50–60%); prismatic lathes, 1 to 3 mm in size, are composed of andesine (An_{37-39}) in the centre and oligoclase (An_{25}) along the edges. 1–2 mm long biotite flakes with sinuate edges are evenly distributed composing 15–17% of the whole rock. Now and then biotite is replaced by chlorite. Quartz grains, 1–2 mm in size, fill interstitial spaces among other minerals. The quartz content is no more than 20–22%. Irregular blotchy blue and green tourmaline grains (1–2 mm in size) with sinuate edges, make up 2–3% of the rock.

Similar plagiogranites form relatively small homogenous bodies of a "spider" shape, surrounded by quasi-migmatite of different patterns formed by intrusion of plagiogranite into contact-metamorphosed mica schist. The plagiogranite here forms 10 to 50% of the migmatite. As a result several rock-types develop: (a) banded migmatite where plagiogranite neosome forms vague 1 cm to 1 m thick intercalations; (b) plagiogneiss where plagiogranite penetrates mica schists with still finer intercalation, enriching them primarily in andesine; (c) feldspathized schist where plagiogranite constitutes no more than 10% of the rock volume and forms very thin lenses of aplitic material. The composition of the intruded material is close to that of the larger plagiogranite bodies. For example the An content of the plagioclase does not decrease below An_{32-35} in both cases.

The Fjortende Julibreen rock-type is a typical leucocratic *granite*, frequently porphyritic and noticeably cataclastic. Medium- and fine-grained granite has a hypidiomorphic granular, slightly posphyritic texture, transformed by cataclasis, resulting even in partial recrystallization of the rock. This mainly affects quartz grains which form lenticular banded alligned aggregates producing a granulitic texture.

The granite is rather simple and constant in composition: almost equal amounts of oligoclase and orthoclase constitute together 65–70%, quartz 25–30%, and biotite in association with subordinate muscovite totals 3–5%. Along with weakly altered orthoclase lathes (1–3 mm in size), substantially saussuritized and sericitized, fine lathes 1–2 mm albite-oligoclase (An_{14-15} to An_{19-20}) make up the rock matrix. Between the feldspar lathes theie are irregular quartz grains (1–1.5 mm) with sinuous outlines and strong undulatory extinction. A granitic porphyritic structure is caused by larger (5–6 mm) orthoclase lathes. Matic minerals are exclusively represented by closely associated fine (1 mm) biotite and muscovite flakes. Muscovite is always developed after biotite and associated with appearance of fine-grained opaque aggregates along the cleavage planes of mica. Fine (0.5 mm) apatite crystals are uniformly distributed over the whole rock.

Cataclasis is manifested not only as partial recrystallization of granite, but with intense saussuritization and albitization of plagioclase, as albite (An_5) occur with oligoclase (An_{15}). Muscovitization of biotite belongs to the same category of secondary processes. The granitic texture changed during intense cataclasis, often attaining a gneissose habit and so this rock-type may be formally called gneissose granite or even "metasomatic" granite.

Similar granite not only forms separate small massifs, but more often forms small (10–100 m in width) irregularly formed bodies with sinuous outlines elongated in one direction and oriented quite concordantly with their enclosing strongly contact-metamorphosed schists and quartzite. Examination of the rocky glacier flanks for a distance of more than 1 km reveals that no less than 60% of the outcrops is composed of granite while less than 40% consists of contact-metamorphosed rock.

These intrusions of granite indicate, firstly, the plastic state of the enclosing rock and, secondly, the high mobility and the rather low viscosity of the granite melt. The enclosing phyllite, schist, interbedded quartzite and marble are laterally "impregnated" with granite melt and therefore they are not only contact-metamorphosed, but transformed into a gneiss or migmatite-like rock. This situation arises in fracture zones at a relatively shallow erosion level when the formation of homogeneous granite bodies is prevented by the physical state of the country rock and accounts for the penetration of the fine intrusions of mobile granite melt into the country rock.

Granite in the upper Kronebreen and Conwaybreen differs from the two above-described granite types in exhibiting (a) cataclasis and gneissification; (b) increased deuteric alteration of plagioclase in particular; (c) formation of new sillimanite (fibrolite) and very small relict fragments of garnet; (d) considerable predominance of oligoclase over orthoclase; (e) a higher (for normal granite) content of biotite (sometimes chloritized) with zircon inclusions. This granite outcrops for a distance of more than 2 km; it is very homogeneous and contains comparatively rare skialiths of contact-metamorphosed schist as 100–150 m thick units, and hornfels xenoliths, 10–20 cm to 2 m in size. These occur within granite bodies as discontinuous chains constituting up to 10% of the granite volume.

A typical rock type is cataclastic and gneissified fine-grained, sometimes prophyritic, granite. Its texture is hypidiomorphic granular, broken down by cataclasis. A porphyritic texture is caused by 5–10 mm lathes of orthoclase and, rarely, plagioclase. The porphyritic phenocrysts cut the pseudo-gneissosity of the rock and have not been subject to cataclasis. The granite is typically composed of: oligoclase (An_{19-23}), 30–40%; orthoclase, 10–20%; quartz, 25–30%; biotite 10–20%; sillimanite (in places) 2–6%; locally detrital garnet — up to 1%; accessories, zircon and apatite and rare needles of rutile.

Cataclasis mainly affects quartz, 1–2 mm long flexuous-flattened grains of which have indented outlines and a strong undulatory extinction. 1–2 mm plagioclase lathes are intensely sericitized, but not broken down. Finer tabular orthoclase grains are materially kaolinized. The granite owes its gneissic appearance to alligned banded-chain-shaped aggregates of biotite flakes (up to 2 mm in length), including many rutile needles and small zircon grains with pleochroic haloes. Biotite flakes are sometimes decolourized, and often chloritisized. Sillimanite forms separate banded aggregates of fine needles of fibrolite type, which cut the rock as 1–2 mm thick discontinuous lenses and chains. Fine (0.1 mm) fragments of garnet grains, occur locally and sometimes form aggregations up to 1 mm in size. There is no doubt about the relict nature of the garnet, and the sillimanite aggregates appear to have originated from inclusions of mica schist.

Individual exposures are made up of massive and weakly cataclastic, medium- or fine-grained, slightly porphyritic biotite-granite. Biotite-granite forms more homogeneous intrusions devoid of gneissosity and xenoliths of country rock. These more massive granites differ little in composition from cataclastic and gneissified ones. For example, oligoclase (An_{20-21}) accounts for 40–50%; orthoclase, up to 20%; quartz, 30%; biotite, 8–12%. However, inclusions of sillimanite and garnet do not occur, and zenoliths of country rock are very rare.

As a whole, in spite of the differences in composition and structure of granitoid rocks in the area, they are the products of crystallization of granite melt which was capable under those geological conditions of active intrusion and caused partial contamination and contact metamorphism of the country rock.

CONTACT-METAMORPHIC ROCKS

During the crystallization of the granite melt, the adjacent Riphean phyllitic schist, quartzite and marble (the lower Hecla Hoek succession) were affected in various ways. As well as the thermal influence of the melt and the addition of volatic components from the melt to the country rock forming hornfels and contact-metamorphosed schist, fine injection of the melt into the country rock followed by crystallization occurred, resulting in the formation of a quite different migmatite-like rock. The contact processes were complicated by the fact that they occurred both in the exocontact zones and internally, in skialiths and xenoliths of country rock. As a result a rather complex group of rocks has formed, which, if studied without due attention, may be identified as gneiss, migmatite, metasomatic granite, etc., varying enormously in composition. As a consequence ABAKUMOV (1976) described pseudo-ultrametamorphic rock of high-grade regional metamorphism instead of true contact-metamorphic rock.

A gradation from normal two-mica schist to contact-metamorphic rock was observed on the Kollerfjorden coast almost along its contact with the glacier. At a distance of 1.5–2 km from the granite body a standard two-mica schist is exposed. This contains no plagioclase, and consists of almost 50% fine (0.03–0.1 mm) weakly recrystallized silt-size grains of quartz, the other 50% being composed of biotite and muscovite aggregates with fine garnet fragments. The occurrence of fine tourmaline crystals is the only indication of the proximity of the granite body.

At approximately 1 km from the granite intrusion, the schist undergoes fundamental changes. It is essentially recrystallized, although the size of grains does not change and 0.1 mm isometric quartz grains still make up no less than half of the rock. The main characteristic feature is the appearance of tabular zoned plagioclase grains (0.2 mm in size), composing 20–25% of the rock. A reverse zoning, with andesine (An_{33}) cores and more basic rims (An_{40}) is frequent. The neogenic character of plagioclase, associated with contact metamorphism, is obvious. This rock type is technically not a plagiogneiss. Another indication is the gradual disappearance of muscovite which is almost completely replaced by biotite (up to 30% of the rock volume) under contact metamorphism. Recrystallization of the rock is manifested, firstly, by the typical hornfels texture owing to the formation of more isometric granules of salic minerals, losing their detrital habit, and secondly, by a uniform distribution of 0.1–0.2 mm long well formed biotite flakes over the whole rock, instead of the former banded aggregates in the mica schist.

Further alteration of mica schist under contact metamorphism is shown in an increase of plagioclase content. Its An-content (An_{35-37}) is identical to that of the adjacent plagiogranite, and its volume increases to 40–50%. Fibrolite aggregates appear in amounts reaching 7–8%; muscovite, confined to 2–3%, gradually disappears; isolated cordierite grains and more abundant fine tourmaline crystals appear. The process of schist recrystallization becomes more active and, as a result, dimensions of the mineral grains especially quartz, increase up to 0.2–0.3 mm and they lose their detrital texture. The rock gradually loses its schistosity and becomes more compact resembling fine-grained plagiogneiss in appearance, although biotite flakes do not form banded aggregates, but are uniformly distributed.

Less than 200–300 m from the intrusion, the mica schist turns into a typical hornfels, with a matrix composed of equidimensional 0.2–0.4 mm isometric quartz granules and tabular grains of andesine (An_{30-32}) totalling 70–75%. The content of biotites become larger (up to 1 mm in length), bright-brown and alligned; the indistinct schistosity of hornfels is a characteristic feature. Fine (0.2–0.4 mm) granules of cordierite and thin aggregates of fibrolite (up to 10%) increase steadily. Apatite, tourmaline and ore minerals often total 2–3%. Recrystallization of the rock manifests not only in increase of grain size, but the rock loses its heterogeneous lepido- and granoblastic texture, and attains a typical hornfels texture. The relict schistosity is not pronounced, typical gneissification is absent and hornfels is represented by a rather dense, uniform rock, very different from gneiss, although it was formerly associated with plagiogneiss in composition. The gradation from two-mica phyllite-like schist to hornfels, observed over many hundreds of metres, rule out its identification as plagiogneiss of amphibolite-facies regional metamorphism (Abakumov 1976).

The gradation from the phyllitic schists of the Signehamna Formation to contact hornfels applies for the whole area and not just in places where hornfels is faulted against the country rock. Some tens of thin sections of the contact rock have been studied to verify that it is not regionally metamorphosed. The dense, rather uniform contact rock is as a rule extremely fine-grained, slightly cataclastic and resembles gneiss slightly, especially when it is not impregnated with granite veins; but even this is closer to migmatite and its nebulitic varieties.

In the contact zone varieties prevail with relict schistosity largely owing to aligned biotites. Biotite flakes, sometimes with torn rims, are variable in size — from 0.1 to 0.8 mm long; and the nearer the rock to granitoid, the lighter the colour of the biotite. Muscovite flakes are preserved only in samples taken at a distance from the contact, and gradually disappear towards the contact. The contact rock is enriched in cordierite and fibrolite, and they are almost constantly present in the so-called skialiths and xenoliths of the former mica schist.

Contact-metamorphosed mica schist is characterized by a rather constant composition: plagioclase — 30–40%; quartz — up to 40%; biotite — 15–25%; the remaining minerals (cordierite, fibrolite, garnet) account for 2–10%. The plagioclase composition of the contact metamorphosed schist is not constant and depends on that of the adjacent granitoid. For example, in the Kollerbreen contact-metamorphic rock, plagioclase is represented only by andesine varying from An_{30} to An_{40}; in the Fjortende Julibreen rock, plagioclase belongs to acid oligoclase (An_{14-18}); and in the Kronebreen contact rock it is represented by typical oligoclase (An_{22-28}). The second peculiarity of the contact metamorphosed schist is the presence of fragments of relict garnet, which never form good crystals; temperatures of contact metamorphism were probably not high enough for recrystallization of terrigenous almandine garnet.

These salient features confirm that (a) contact-metamorphic rock has formed from mica schist and therefore it retains relict garnet, and (b) processes of contact metamorphism are closely associated with the intrusion of granite melt, and therefore the composition of the plagioclase is related to that of the adjacent granite intrusion.

Concluding the description of contact-metamorphic schist it is necessary to emphasize that, where cataclasis is more developed, biotite is partially replaced by chlorite with formation of thin ore aggregates; plagioclase is essentially sericitized; and quartz grains have strong undulatory extinction and tend to form flattened and thin lenticular aggregates of granulitic texture.

Typical hornfels occurs mainly as skialiths within the granitoid. It is characterized by the appearance of orthoclase, when skialiths occur in two-feldspar granite; but when included in plagiogranite, hornfels is devoid of orthoclase. Orthoclase-bearing hornfels does not contain cordierite. Generally this rather uniform rock is represented by biotite hornfels of the following composition: plagioclase 30–50%; orthoclase 0 to 25% (content of plagioclase decreases respectively); quartz 30–35%; biotite 15–20%; accessories include rare crystals of tourmaline and ore minerals. Isolated occurrences of hornfels retain fine (0.05 mm) fragments of garnet, with chlorite rims. The hornfels is a very dense fine-grained rock, and isometric grains do not exceed 0.2–0.3 mm in size. Quartz has a strong undulatory extinction and plagioclase is sericitized. Plagioclase composition in hornfels depends on that of the enclosing granitoid as was described for contact metamorphic schist.

In highly cataclastic hornfels varieties, intense sericitization of plagioclase and chloritization of biotite has taken place. Although 0.2–0.4 mm long bright-brown biotite flakes are elongate, they are uniformly spaced in the rock. The rock texture is typical hornfels (pavement) because of the equidimensional isometric grains of adjacent salic minerals. Only orthoclase segregations, larger and more irregular than the main granular matrix, look neogenic.

The small (up to 1 m in size) xenoliths in the granite vary in composition. Common biotite hornfels, sometimes with orthoclase inclusions, predominates. Another rock-type containing hornblende, garnet, and sphene, occurs in xenoliths. This is rather unusual in composition: sericitized andesine (An_{34-35}) 30%; quartz 15%; orthoclase 15%; green hornblende 17%; garnet 6%; sphene 3%; biotite 7%; ore minerals 4%. Its texture is heteroblastic, locally idioblastic or granoblastic. Only segregated orthoclase and brown well formed biotite flakes may be neogenic. All other minerals, though recrystallized, may have relict nature; this especially is true for 1 mm skeletal grains of garnet and ore minerals. This rock-type may be dervied from a basic rock, accounting for the occurrence of sphene, garnet and amphibole along with rather basic plagioclase. Amphibole rarely occurs in the contact rock in this area, or in the mica schists of the Signehamna Formation.

Individual interlayers of *quartzite* within mica schist were also subject to contact metamorphism, especially if they occur in skialiths. This hornfels is distinguished by the abundance of quartz (60–75%) in fine (0.1–0.2 mm) isometric grains, resulting in a pavement texture. A second feature is a rather acid persistence of fine grains of cordierite and bundles of fibrolite (altogether 15–20%). Another feature is a leucocratic composition, biotite flakes constituting less than 5%.

Marble interlayers undergo pronounced contact metamorphism, especially when they are included in skialiths. In the contact calciphyre the percentage of preserved carbonate reaches 20–50%, giving way, first of all, to diopside (30–60%) and then to wollastonite (6–8%), and amphibole (3–10%). In the calciphyre, sphene is always present, but in small amounts (1–2%). Diopside forms 1–2 mm prismatic crystals, constituting the matrix. Wollastonite aggregates and more irregular prismatic grains of amphibole are included in these rocks. Isometric granules of calcite (0.3–0.6 mm in size) fill the intersticies. Fine (0.1–0.2 mm) sphene crystals occur throughout.

Thin veins of aplite and thicker veins of pegmatite cut both granite and country rock. Migmatite-like rock occurs in skialiths and in exocontacts of granite bodies.

Palaesome of pseudo-migmatite is contact-metamorphic mica schist, while neosome is represented by plagioaplite or leucocratic normal granite, and sometimes even by conformable quartz veinlets.

Extremely finely-layered migmatite, taken for gneiss in the field, outcrops along the Kollerbreen. Study in thin sections shows that 5–6 mm thick layers of palaeosome consist of fine-grained cordierite-biotite-hornfels (with high content of biotite up to 30% and equal quantities of fine 0.2–0.3 mm granules of cordierite and quartz — 10–15% each), while neosome consists of indented 2–3 mm grains of quartz 80% and sericitized lathes of andesine (An_{32-33}) — 20%. Generally, the composition of the neosome is identical to that of the granite, in which the skialiths occur.

Study of composition of numerous skialiths, granite bodies, and the country rock reveals that contact-metamorphics of the anthophyllite-cordierite subfacies of the amphibolite facies are distributed in the study area within the narrow subfracture zone. Four paragenetic mineral associations of this subfacies occur.

(1) muscovite-biotite-plagioclase-orthoclase-quartz;
(2) biotite-amphibole-plagioclase-orthoclase-quartz;
(3) diopside-amphibole-wollastonite-quartz;
(4) muscovite-biotite-cordierite-plagioclase-quartz.

The last association is most widespread, while the second is least common. Association of diopside with wollastonite and amphibole is only typical of contact-metamorphic marble. Almandine is not inherent in the anthophyllite-cordierite subfacies, where it is generally replaced by cordierite. Sillimanite is also not characteristic of this subfacies, but its low-temperature variety, fibrolite, can occur when the original rock was oversaturated with alumina.

The anthophyllite-cordierite subfacies of the amphibolite facies is typical of contact-metamorphic rocks, while all other subfacies of amphibolite facies, staurolite-kyanite, sillimanite-almandine and almandine-diopside-hornblende are characteristic of regional-metamorphic rock. These three subfacies do not occur in the study area. Therefore, these metamorphic rocks are not part of a granite-gneiss or gneiss-migmatite complex of ultrametamorphic genesis, as was formerly put forward by KRASIL'ŠČIKOV (1973).

Chemical composition

The chemical composition of the three main granitoid types of the area, Table 1, confirms the above conclusions made in the petrography.

Granitoid from outcrops along the Conwaybreen (sample 23-v) are represented by a normal two-feldspar granite, with a composition practically unaffected by cataclasis and gneissification. The leucrocatic nature of granite from the Fjortende Julibreen outcrops (sample 14-ž) is reflected by the low percentage of mafic components (especially FeO and MgO) and the high content of alkalis. Na_2O and K_2O constitute up to 8%, closely approaching the alkali content in granosyenite. Plagiogranite from outcrops along the Kollerbreen (sample 10), approaches the composition of granodiorite, differing greatly from the two rocks described above. The SiO_2 content is low at 64.7%. The FeO and MgO contents are twice as high compared with granite; and there is a low content of K_2O, only 2.2%, reduced from approximately 4% in a normal granite.

It is interesting to compare the chemical compositions (Table 1) of phyllite surrounding granites of the lower part of the Hecla Hoek succession with hornfels xenoliths formed within granite. The influence of contact metamorphism on phyllite of the lower Signehamna Formation in the Kollerfjord area is especially clear. At 1.5 km from the plagiogranite body of the Kollerbreen, two-mica schist (sample 3) almost unaffected by contact-metamorphism is exposed; it consists of almost equal amounts of aggregates of sericite, fine

Table 1

Chemical compositions of rocks of the North-Western part of Spitsbergen.

Ord. Nos.	Sample Nos.	Name of rock	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	MnO	K_2O	Na_2O	P_2O_5	H_2O	Total
		Granitoid													
1.	10	Plagiogranite (transitional to granodiorite)	64.70	0.68	16.67	0.07	4.83	3.81	2.19	0.09	2.20	3.55	0.27	0.86	99.92
2.	14-ž	Leucocratic granite	72.35	0.16	14.27	0.12	1.92	1.23	1.02	0.04	4.88	3.38	0.09	0.63	100.09
3.	23-v	Gneissified granite	73.19	0.36	13.20	—	3.10	1.20	1.63	0.04	3.78	2.65	0.11	0.77	100.03
		Country rock (phyllite)													
4.	3	Two-mica schist (phyllite)	65.21	0.90	16.75	0.33	4.92	0.70	2.66	0.08	4.63	1.70	0.08	2.01	99.97
5.	16	Mica schist (meta-argillite)	67.25	0.78	15.11	0.35	4.09	1.01	2.11	0.09	4.34	2.61	0.12	1.84	99.70
		Contact metamorphosed rock													
6.	5-a	Contact — metamorphic schist	69.57	0.74	13.72	0.52	4.17	1.14	2.19	0.06	3.64	2.22	0.09	1.68	99.74
7.	31	Contact — metamorphic schist	67.09	0.80	14.97	0.27	4.97	1.55	2.50	0.07	2.45	4.00	0.15	1.02	99.84
8.	9	Schistose hornfels	69.48	0.63	13.38	—	5.55	2.16	2.05	0.09	2.90	2.54	0.11	0.98	99.87
9.	14-v	Schistose hornfels	66.77	0.82	14.70	0.10	5.71	2.34	2.67	0.08	2.60	3.00	0.12	1.22	100.13
10.	28-b	Schistose hornfels	67.13	0.74	14.28	0.24	6.35	1.79	2.42	0.19	2.59	2.71	0.09	1.65	100.18
		Hornfels xenoliths in granite													
11.	32-v	Hornfels in granite	72.29	0.66	11.69	0.69	4.85	0.28	2.68	0.08	2.53	2.19	0.12	1.84	99.90
12.	23-g	Hornfels in granite	74.01	0.59	11.67	0.36	4.13	1.72	1.81	0.07	1.64	3.08	0.10	0.84	100.02

flaky biotite, and silt-size granules of quartz with a small addition of fine feldspar granules. It is characterized by a high content of K_2O (4.63%) and Al_2O_3 (16.75%) and a low content of SiO_2 (65.21%) and Na_2O (1.70%). At a distance of 1 km from the granite body the schist (sample 5-a) undergoes marked changes in composition: SiO_2 rises by 4.36%, while Al_2O_3 and K_2O are lower by 3% and 1%, respectively. The contents of other elements varies slightly within the range of 0.5%. Further changes take place at a distance as near as 200 m from the granite body, when two-mica schist (phyllite) is replaced by typical schistose hornfels (sample 9), resembling gneiss in texture. Compared to moderate contact-metamorphic schist (sample 5-a), typical hornfels (sample 9) differs by having a higher content of FeO and CaO, while content of K_2O decreases by 0.74%, Fe_2O_3 — by 0.52% and Al_2O_3 — by 0.34%. The contents of some other elements also decreases.

The change from almost unaltered mica schist to typical hornfels, as represented by samples 3, 5-a, and 9 is accompanied by relatively small changes in composition shown by higher contents of silica and iron and lower contents of potassium and alumina. However, there is no reason to believe that typical mica schist and contact rock, are gneiss and crystalline schist respectively, or that the contact rock is older. The same is true for hornfels of all other areas which are close in composition (analyses of samples 31, 14-v, 28-b), as they also formed during contact metamorphism of phyllite.

Hornfels zenoliths (samples 32-v and 23-g) occurring within granite, differ from mica schist. They are characterized by an increase in SiO_2 content (by 6–7%), a decrease in Al_2O_3 (by 4–5%), and a lower percentage of alkalis, especially K_2O (by 1.5–2%); the content of alkalis is equal to that of the surrounding granite.

The similarity in chemical composition between mica schist and so-called "gneiss", "migmatite" and "crystalline schist" (that are really hornfels) establishes that they are closely related, and not separate sequences of older Proterozoic rock. All the changes taking place in mica schist near granite bodies are easily explained by the mobility of silica and alkalis and by the increase of thermal gradient in the country rock during the crystallization of granite magma.

Physical properties of the rock

Measurements of density, differential measurements of velocity of propagation of longitudinal elastic fractuation, magnetic susceptibility and specific electric resistance were carried out for three rock groups: phyllite, hornfels and granite. Sonic measurements were carried out on 4–6 mm thick plates. The error of density measurements is ± 0.001 g/cm^2. Relative error of measurements of magnetic susceptibility and of electrical resistivity is not more than 10%.

The comparison of physical properties of three samples, 3–phyllite, 5-a–contact metamorphosed phyllite, and 9–schistose hornfels, is of principal interest. In phyllite (Fig. 2), in spite of its microscopic homogeneity, boundaries of uniform fields of magnetic susceptibility, of sonic speed, and, to a lesser

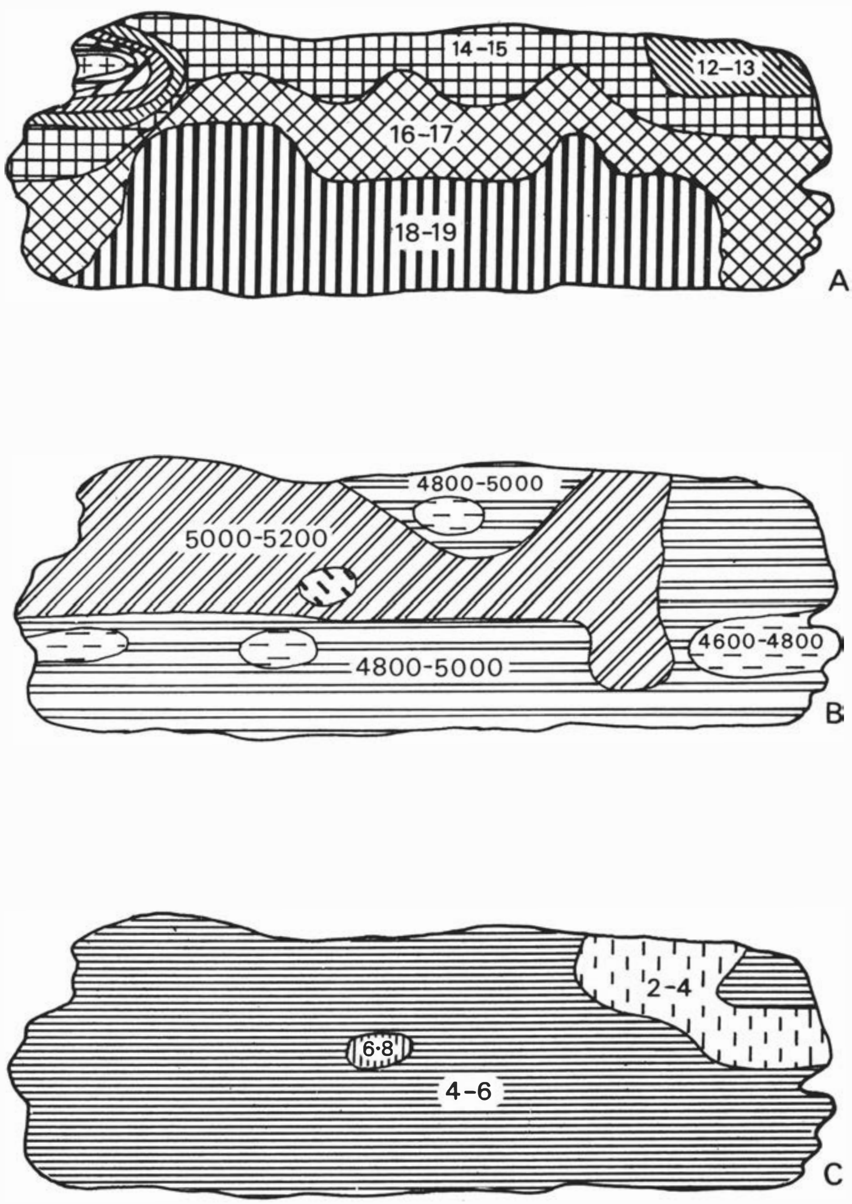

Fig. 2. *Specimen 3* (*½ of natural size*) *: A — distribution of velocity of longitudinal elastic waves* (*m/sec*) *; B — distribution of magnetic susceptibility* (*10^{-6} CGSM*) *; C — distribution of electric resistance* (*10^{5} ohm/cm*).

degree, of electrical resistivity are defined, and they coincide with the direction of schistosity. This may indicate that the given distribution is syngenetic to phyllitization or related to earlier sedimentary texture processes. In the contact-metamorphosed phyllite (Fig. 3) the boundaries change their configurations but still coincide with the direction of schistosity. This is most pronounced for the distribution of magnetic susceptibility. Magnetic susceptibility generally decreases compared with normal phyllite, while electrical

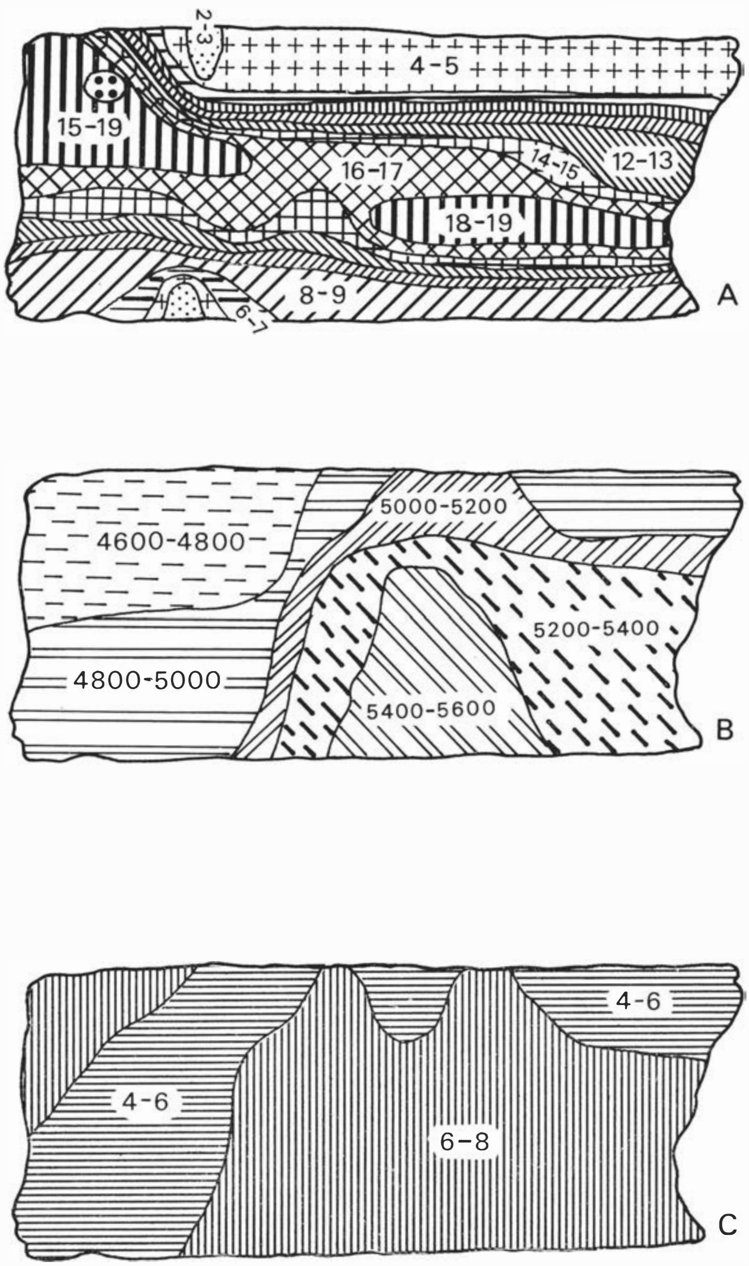

Fig. 3. *Specimen 5-a ($^1/_2$ of natural size) : A — distribution of velocity of longitudinal elastic waves (m/sec) ; B — distribution of magnetic susceptibility (10^{-6} CGSM) ; C — distribution of electric resistance (10^5 ohm/cm).*

resistivity and speed of propagation of longitudinal ultrasonic waves show an increase. Further changes in all these physical properties take place in hornfels (Fig. 4), though their boundaries, as a whole, continue to coincide with the direction of schistosity of the primary phyllite. In this case, the magnetic susceptibility falls, while sonic speed and electric resistance rise. These changes are associated with recrystallization of phyllite during contact metamorphism,

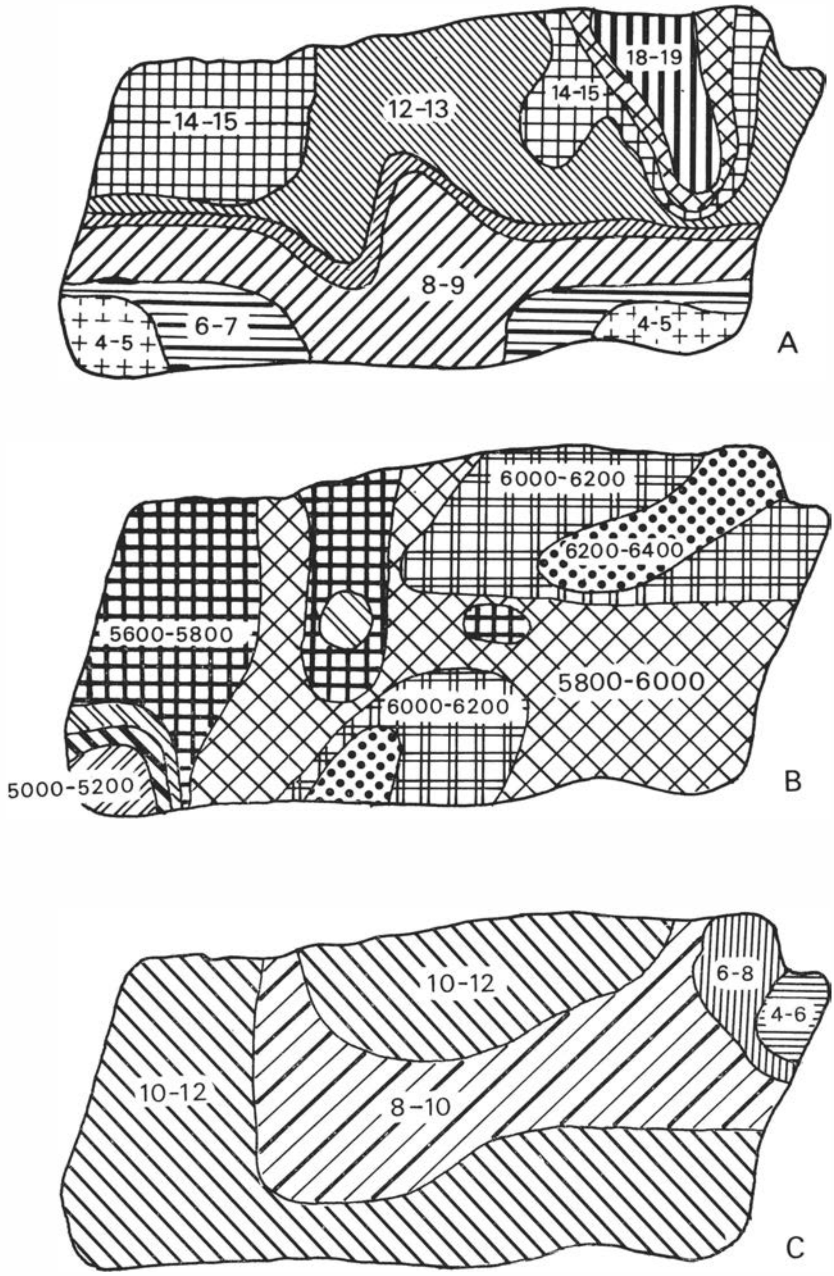

Fig. 4. *Specimen 9 ($^1/_2$ of natural size) : A — distribution of velocity of longitudinal elastic waves (m/sec) ; B — distribution of magnetic susceptibility (10^{-6} CGSM) ; C — distribution of electric resistance (10^5 ohm/cm).*

causing improvement of acoustic contact between grains and raising the electric resistance. Recrystallization leads to ruptures of boundaries of uniform fields in hornfels, and therefore field boundaries in places cut the primary schistosity.

In spite of changes shown above, the majority of physical properties of the three samples, collected from a section along the flanks of Kollerfjorden and the Kollerbreen are so similar, that their close consanguinity is doubtless. The density of the three samples varies from 2.704 to 2.780, decreasing with increase in metamorphic grade. Magnetic susceptibility decreases from 14–19×10^{-6} CGSM to 8–18, while electric resistance increases throughout the complete recrystallization of phyllite to hornfels.

The distributions of these physical properties for the adjacent granite massif (Fig. 5) are given for comparison with the phyllite-hornfels series described above. Granite is characterized by uniform physical parametres and by the absence of differentiation within a sample. Its magnetic susceptibility is much lower and its electric resistance measurements are higher than those of phyllite and even hornfels. Granite is a massive uniform rock, in contrast to phyllite and hornfels, where schistosity causes variation in physical parametres.

Conclusions

Results of careful geological, petrographical, chemical, and petrophysical studies carried out on rocks of the Krossfjorden area by the author during the summer of 1972 and subsequently in 1974, prove that there is no Early Precambrian Kollerbreen Formation, more than 3500 m in thickness, made up of metasomatic granite, migmatite and gneiss, in the study area. In this region the Signehamna and Generalfjella Formations are developed with a total thickness of 8–9 km, representing the lower Hecla Hoek Succession probably of Riphean age. Mica schist (phyllite) with horizons of marble in the upper part prevail.

A fracture in the Krossfjorden area controlled intrusion (during the Caledonian tectogenesis) of granitoid, probably of rheomorphic mass. Crystallization of the magma resulted in the formation of granite and granodiorite bodies and metamorphism of phyllite into hornfels, sometimes with fine injection of granite magma, resulting in a migmatite-like rock. These schistose hornfels and migmatite-like rocks have been taken by previous workers for a regional-metamorphic gneiss-migmatic complex.

K-Ar absolute age determinations on this quasi-gneiss-migmatite rock yield values in the range of 420–440 m.y. (Krasil'ččikov 1973). Additional determinations have been carried out in the laboratory of the Radium Institute of the Academy of Sciences of the USSR. The results obtained are given below.

Sample No.	Rock	K%	Ar $\frac{cm^3}{g} \cdot 10^{-5}$	Age, m.y.	Note
23–I	Hornfels (gneissic)	3.34	6.12	430	The upper Conway-breen
14–ž	Leucocratic granite	4.36	6.89	380	The flank of the Fjortende Julibreen

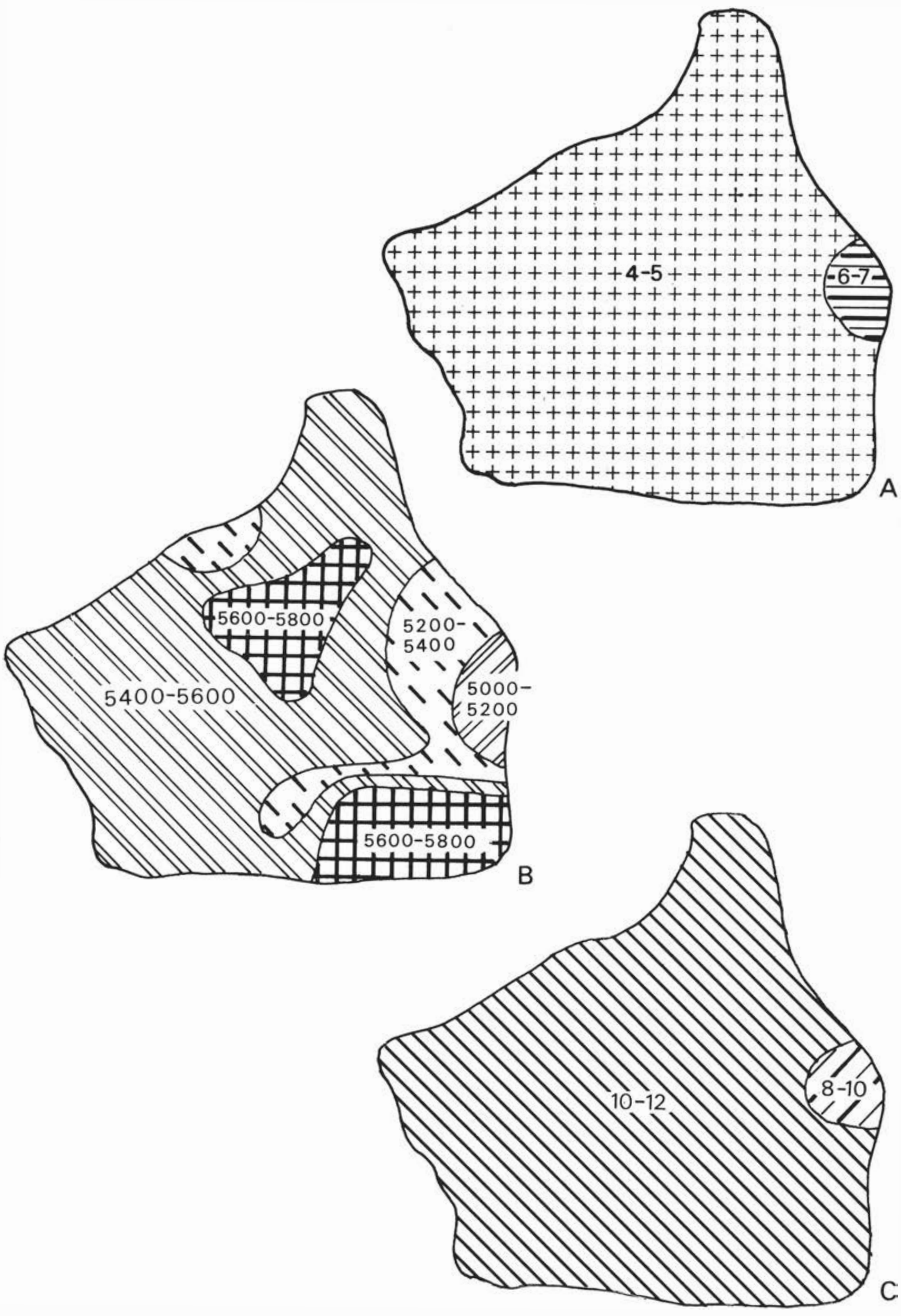

Fig. 5. *Specimen 14-ž : A — distribution of velocity of longitudinal elastic waves (m/sec) ; B — distribution of magnetic susceptibility (10^{-6} CGSM) ; C — distribution of electric resistance (10^5 ohm/cm).*

Thus, the hornfels is 50 m.y. older than granite. This can only be explained by an initial Riphean age for the hornfels which was not quite rejuvenated during contact metamorphism.

Although the band of contact-metamorphic rock traced by the author extends for only 40 km across strike, we think that the age of the so-called Early Precambrian gneiss-migmatite complexes of Spitsbergen should be reviewed, as they may prove to be not the oldest crystalline rocks of the region, but contact-metamorphics associated with Caledonian magmatism. The Caledonian geosyncline of Spitsbergen may have been initiated not within the Early Precambrian basement of Karel tectogenesis, but within the Riphean basement of Baikal tectogenesis, like all the other Phanerozoic geosynclines. The Caledonian tectono-magmatic processes in Svalbard with wide spread development of deep rheomorphism, and associated plutonic activity and metamorphism, is characteristic.

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