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THE LOWER PROTEROZOIC MARMORILIK FORMATION, EAST OF MÂRMORILIK, WEST GREENLAND

BY

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WITH 25 FIGURES AND 7 PLATES

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Abstract

The Lower Proterozoic Marmorilik Formation, West Greenland, is situated in the Rinkian orogenic complex. East of Mârmorilik its predeformation thickness is more than 2 km.

A basal 30–60 m thick clastic unit is followed by over 650 m of banded to massive dolomite marble with accessory calcite, quartz, phlogopite, albite, scapolite, pyrite and graphite; near the base of the formation tremolite is common. Dolomite-calcite marble occurs locally in this unit. The massive dolomite is followed by a thin member of impure calcite marble that is succeeded in turn by ca. 300 m of massive dolomite marble. The upper ca. 650 m of carbonate include ca. 350 m of pure calcite marble. The uppermost 200 m known of the formation consist of semipelite, which also forms thin horizons in the marbles.

East of Mârmorilik the formation is affected by regional metamorphism of greenschist facies grade. The carbonate-silicate parageneses found are isobarically divariant. The estimated temperature and pressure at the peak of metamorphism are up to 500° and 3000 bars.

The general structure of the formation east of Mârmorilik is that of an open syncline with an E–W-trending horizontal axis. There are several internal, recumbent tight to isoclinal folds accompanied by thrusts; these do not upset the overall stratigraphic sequence. Both left-lateral transcurrent and normal faulting has affected the area.

The Marmorilik Formation forms the host rock of the Black Angel Zn–Pb ore deposit, the structural and stratigraphic position of which is discussed. Also small low-grade sulphide mineralisations occur, which consist of sphalerite, galena and pyrite in varying proportions; chalcopyrite, tennantite-tetrahydrite, boulangerite and ullmanite were also found. The mineralisations are stratabound, but some mobilisation has occurred during deformation and metamorphism. Analyses of Zn, Pb, Cu, Ni, Fe, and Mn from ordinary marbles are presented. The origin of the base metals is syn- or epigenetic.

Little evidence is left concerning the origin of the marbles; the calcite marbles may well be remnants of a primary calcium carbonate precursor, and the dolomites are believed to have formed by dolomitisation of the refluction type. There is no reason to invoke other processes in the formation of the carbonates than those that are known to have operated during the Phanerozoic.

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I. INTRODUCTION

General

The Marmorilik Formation, West Greenland, is an extensive, near to 2 km thick, Lower Proterozoic carbonate succession, which has been metamorphosed under greenschist to amphibolite facies conditions. Large, Early to Middle Precambrian carbonate formations are not common throughout the world, and in the Precambrian of Greenland the Marmorilik Formation is unique. Near the mining-town Mârmorilik, a former marble quarry, the Marmorilik Formation forms the host rock of the Sorte Engel (Black Angel) Zn-Pb ore deposit; it is also the largest potential source of calcium carbonate on the west coast of Greenland.

Being chemical or biochemical sediments, carbonates play an important role in the early sedimentary record of the world, as they best reflect the chemical constraints in the hydrosphere at the time of their deposition. Thus a knowledge of the original composition and geological setting of the Marmorilik Formation is of general interest in relation to the Precambrian evolution of the earth.

The aim of this paper is to present a general description and a 1:20000 map of the Marmorilik Formation in the area east of Mârmorilik, where the formation is best preserved; to provide an estimate of the original thickness of the carbonates on the basis of their present structure and stratigraphy, and to discuss the origin of Zn-Pb sulphides (including the Sorte Engel ore body) in the formation on the basis of the character and distribution of the mineralisations found in the field.

Geological setting

The Marmorilik Formation is situated in the Umanak district, West Greenland, around 51° W, 71° N (Figure 1) in a coastal area with alpine relief, consisting of peninsulas and islands with plateaus ranging in altitude from 600 to 1400 m above sea level, separated by deep fjords. The Precambrian in this area belongs to the Rinkian orogenic complex, accounts of which have been published by Henderson & Pulvertaft (1967), Henderson (1969), Pulvertaft (1973), and Escher & Pulvertaft (1976).

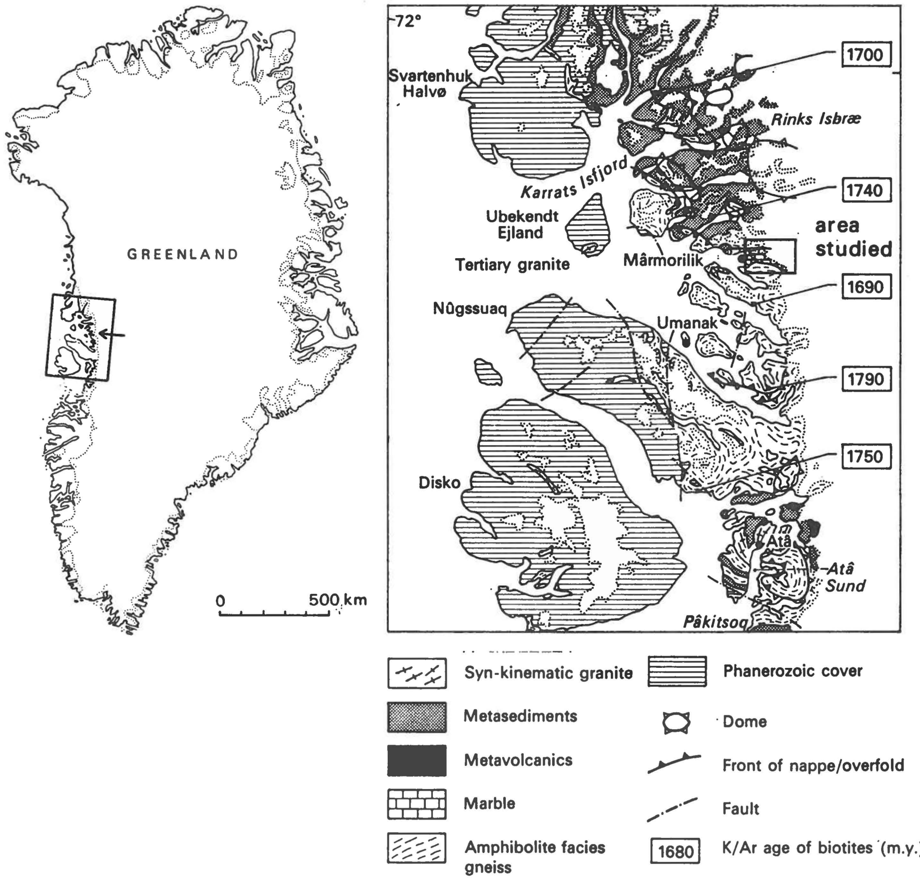


Fig. 1. Position and geological sketch map of the southern and central part of the Rinkian mobile belt, with the location of the area studied east of Mârmorilik (modified from ESCHER & PULVERTAFT, 1976).

Formerly the Marmorilik Formation was thought to be an integral part of the basement unit in the region, the Umanak gneiss. Later field work by T. C. R. PULVERTAFT in 1975 and the writer in 1974–1975 has revealed that the Marmorilik Formation rests unconformably on the basement rocks (GARDE & PULVERTAFT, 1976).

The minimum age of the Marmorilik Formation is set by potassium-argon age determinations by LARSEN & MØLLER (1968) on biotites from gneisses, pegmatite veins and metasediments in the district, which give ages from 1690 to 1790 m.y.; these ages probably reflect the close of metamorphism and deformation. The maximum age is more vaguely defined: the Marmorilik Formation is younger than the granite-gneiss complex on which it is deposited, and which is believed to be of Archaean age (PULVERTAFT, 1973, p. 537); recently the age of the large granodiorite body which forms the basement in the area considered here has been dated by F. KALSBEEK to 2615 ± 100 m.y. (preliminary results, rubidium-strontium whole rock analyses). Probably the Marmorilik Formation itself is not Archaean, and in view of present knowledge likely to be about 2000 m.y. old.

Topography in the area east of Mârmorilik

The best preserved and most accessible part of the Marmorilik Formation is situated east of the narrow fjord Agfardlikavsâ. It is bounded by the Inland Ice to the north and east, and by basement rocks to the south (Plates 1 and 7). The southern part of this area forms a plateau with a moderate relief and elevations from roughly 600 to 900 m above sea level, and with several large lakes. Towards the north the topography rises up to 1000–1100 m above sea level, where the front of the ice-cover is met; an ice-free plateau at this elevation continues on the "Black Angel mountain" to the north-west, where it ends abruptly in steep, inaccessible cliff-sides facing Agfardlikavsâ and Qaumarujûp qíngua.

The rocks are very well exposed except on the highest plateau, where the ground is almost completely covered by moraine and loose flags of the bedrock.

Mapping and topographic base

During the summers 1974 and 1975 mapping was carried out on enlarged aerial photographs, scale ca. 1:10 000. Because no proper topographic map of the area was available, a new map in scale 1:20 000 with 25 m contour intervals has been prepared photogrammetrically; in the same process the geology was transferred from the enlarged photographs used for mapping, resulting in as accurate a geological map as can be prepared at the scale used. The aerotriangulations were made by K. S. DUEHOLM employing a method developed by him which only demands a very limited number of trigonometric stations in the field (DUEHOLM et al., in press). For further details see Plate 7.

II. STRATIGRAPHY

Procedure followed in establishing the stratigraphy

The Marmorilik Formation has an estimated total predeformation thickness of ca. 2000 m in the area described here and consists mainly of dolomite and calcite marble.

The formation has been divided into 7 lithostratigraphic members

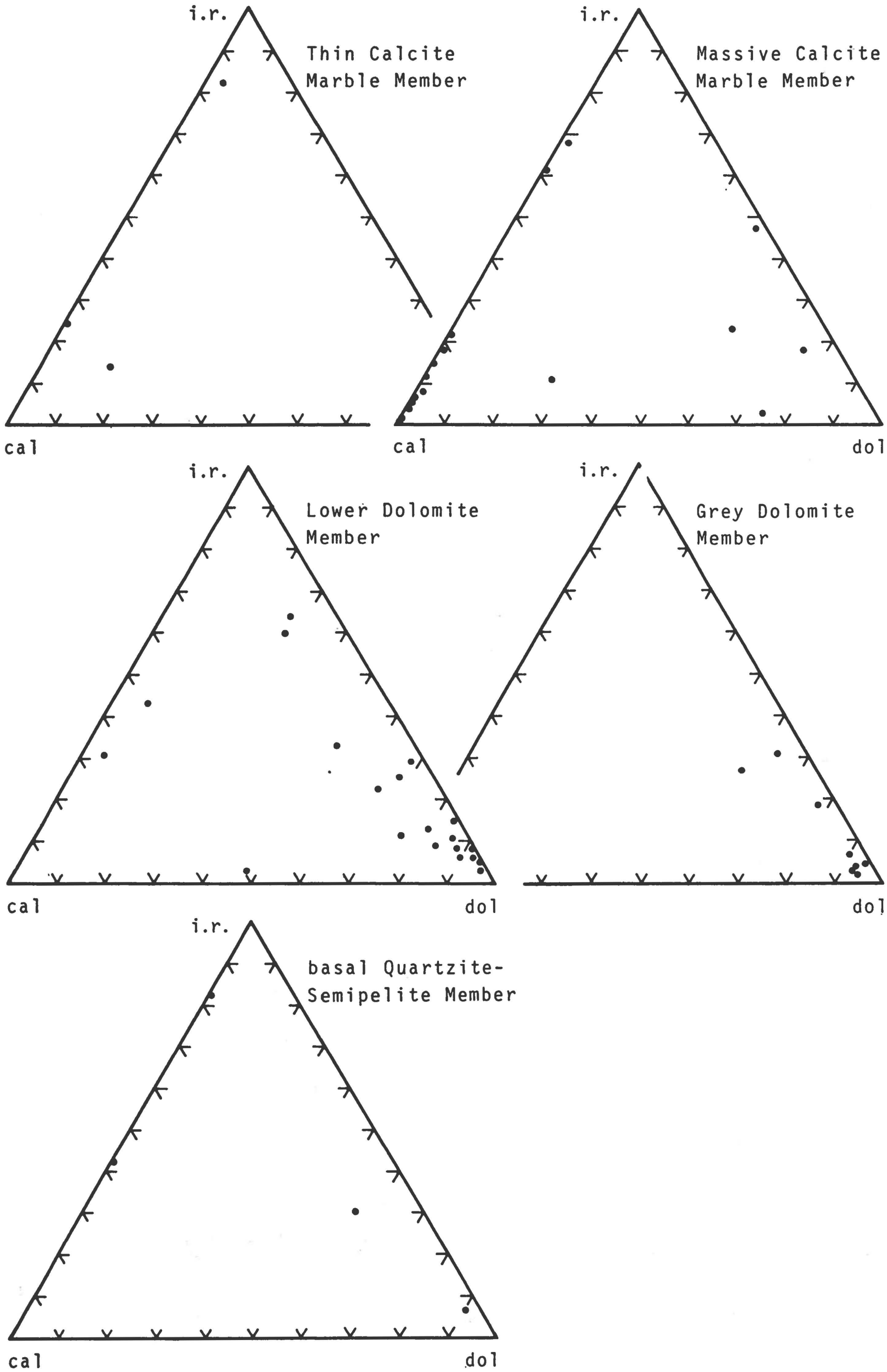


Fig. 2. Proportions of calcite (cal), dolomite (dol), and acid insoluble residues (i.r.) in marbles and calc-silicate rocks (with more than 15 % carbonates) from various members of the Marmorilik Formation. The diagrams include samples of secondary origin, and unusual rock-types are generally overrepresented.

(see Plate 6) in the area east of Mârmorilik along three type sections which together cover the complete stratigraphic sequence known. The locations of the type sections are as follows (Plate 7): 1) starting at the type locality of HENDERSON & PULVERTAFT (1967) at the 915 m top and proceding towards the north-east to the 480 m lake, 2) along the ENE–WNW-trending ridge 1–1.5 km south-east of the 480 m lake, starting in the corner between three fault blocks, 3) from the north-west corner of the 470 m lake towards the north uphill to the ice cap (approximately following the section E–F on the map).

The division of the marble into members is based on lithological differences recognisable in the field such as composition, interbanding with other rock-types, and in some cases colour and texture. The formal division has been carried out only to such an extent that each member is dominated by one, or a couple of, characteristic types of rock, but with allowance for some lateral and vertical variations. A finer division would probably not serve its purpose as a tool in correlation, especially with other areas, and would anyway be lost in the more strongly folded sequences. Individual semipelite horizons within the marble have not been given the rank of members because they are difficult to distinguish from each other, because their thickness is usually only 4–10 m, and because they are not characteristic of any particular succession (unlike the semipelite-banded marble, see p. 18, which forms a characteristic rock-type at certain stratigraphic levels, and the thick semipelite unit terminating the formation).

Deformation and facies variations along strike make exact correlation difficult; however, in the area described correlation is reasonably good in the lower part of the formation (see Plate 6), where distinct semipelite beds serve as marker horizons. During mapping the distribution patterns of dolomite and calcite marble proved to follow the trends of the clastic markers, and in consequence the various types of marble could be used for further stratigraphic division and correlation.

The calcite and dolomite proportions of marbles throughout the area have been determined by X-ray diffraction (see e.g. ROYSE et al., 1971), and their content of acid insoluble material by the carbonate bomb (MÜLLER & GASTNER, 1971). In the field the distinction between calcite and dolomite was facilitated by staining with Alizarine Red S (MÜLLER, 1967). The proportions of calcite, dolomite and acid insoluble residues in marbles from various members are shown in Figure 2.

Weathered calcite rocks of the Marmorilik Formation in the area concerned generally have smooth, rounded outcrop surfaces, which on closer inspection are seen to be marked by the weathering of individual ca. 1 mm large grains. Dolomite rocks, of the other hand, have grain sizes under ca. 0.3 mm (except in secondary veins), and — particularly when quartz-rich — weather out into irregular blocks with sharp edges, and surfaces like fine sandpaper. In areas of the Marmorilik Formation where amphibolite facies metamorphic conditions have been reached, however, the dolomite has frequently grain sizes over 1 mm.

Summary of the stratigraphy of the Marmorilik Formation

On Plate 6 a generalised stratigraphic column of the Marmorilik Formation is presented with estimated pre-deformation thicknesses. The column has been compiled from several selected profiles where the various parts of the succession are well developed, and where modifications due to deformation could best be taken into account. It is seen that the stratigraphic sequence in the lower half of the formation is relatively constant along strike. The total predeformation thickness of the formation is estimated to not less than 2 km, based on a correlation between the least disturbed successions in various profiles. The reader is referred to the map (Plate 7), the stratigraphic descriptions that follow and the section on structure for details and discussions about correlation, division into members, predeformation versus present thicknesses, etc., in particular p. 39 concerning the thickness of the calcite marble occurring in the upper part of the formation.

The stratigraphy of the Marmorilik Formation in the area east of Mârmorilik may be summarised as follows:

The formation rests unconformably on a granodiorite belonging to the Umanak gneiss complex. The basal ca. 60 m thick succession, the Quartzite-Semipelite Member, consists of predominantly clastic rocks, beginning with orthoquartzite with local cross-bedding and wave ripple-marked surfaces preserved and occasional pockets of conglomerate as well as magnetite quartzites (heavy sands), and continuing up into calc-silicate rocks, often rich in tremolite, and finely laminated semipelite.

The basal clastic rocks grade into the more than 650 m thick Lower Dolomite Member, which begins with a sequence of impure siliceous dolomite marble up to ca. 200 m thick. Tremolite is only common in the lowest 50–250 m of the Lower Dolomite Member, soon followed by coexisting dolomite and quartz. The siliceous dolomites contain calcite in amounts of 10–15 $^0/_0$ of the total carbonate and around 25 $^0/_0$ acid insoluble silicate residues. Above the siliceous dolomite marbles follows almost pure dolomite marble, the larger part of which is massive to weakly banded and fine-grained, and contains 5–10 $^0/_0$ calcite and ca. 10 $^0/_0$ silicates, mainly quartz, phlogopite and albite. Pyrite as well as finely disseminated graphite are common, and there are occasional sphalerite (-galena-pyrite) mineralisations within clearly defined stratigraphic intervals. Apart from bedding surfaces no primary sedimentary structures have been found in marble. Towards the top of the Lower Dolomite Member there are several dolomite marble beds with 20–40 % quartz as well as a few metres thick unit of dark grey banded dolomite-calcite marble.

Two persistent dark grey, rusty semipelite horizons with thicknesses ranging from 2–15 m occur in the Lower Dolomite Member, and similar horizons occur in the upper units.

The dolomite marbles described above are followed by the 20–40 m thick Thin Calcite Marble Member, which consists of light yellow, fine- to medium-grained calcite marble containing up to 25 % dolomite, bounded by dark calcite-dolomite-semipelite rocks with a compositional banding on a cm-dm-scale.

This thin calcitic unit is overlain by ca. 300 m of monotonous grey fine-grained, nearly pure dolomite marble, the Grey Dolomite Member, with occasional quartz-bearing horizons and a couple of semipelite horizons. Sphalerite mineralisations, sometimes with galena and pyrite, were occasionally found in this unit.

The Banded Marble Member with a total thickness of ca. 150 m succeeds the Grey Dolomite Member and consists of ash-grey, graphite-bearing dolomite, dolomite-calcite and dolomite marble, often quartz-bearing, and with several very fine-grained, massive, buff to light grey cherty quartzite horizons about one metre thick.

The upper ca. 500 m of carbonate, the Massive Calcite Marble Member, is dominated by massive, yellow to grey, mm-grained, calcite marble with phlogopite; there are also semipelite-banded calcite (-dolomite) marble and some quartz-bearing, white to buff dolomite marble horizons. The calcite marble has an estimated predeformation thickness of ca. 350 m; it generally contains less than 1 % dolomite and 2–10 % acid insoluble residues.

Above the marble follows the at least 200 m thick Semipelite Member. The semipelite is laminated on a mm-scale, fine-grained, dark grey and consists mainly of quartz, biotite, muscovite and albite with accessory pyrite, sometimes pyrrhotite, and graphite. Calcite and dolomite are almost or completely absent. The upper stratigraphic boundary of the Marmorilik Formation is unknown.

Basement and the basal unconformity

The general structure of the area east of Mârmorilik is that of an open, E–W-trending syncline, separated by sinistral faults into several blocks. Along the southern flank the basal contact of the Marmorilik Formation dips 15–40° to N–NE and can be followed on foot for ca. 10

km, but on the northern flank the southward-dipping contact is only exposed for about 200 m. Everywhere the basal quartzite of the formation rest of a bevelled, weakly undulating surface of coarse biotite-(sphene-) granodiorite with feldspar megacrysts. The granodiorite surface does not exhibit any features that can be ascribed to Precambrian weathering.

The granodiorite is uniform and generally little deformed, but it may show a strong contact-parallel foliation which dies out a few metres away from the unconformity. The granodiorite contains several, 1–5 m thick metabasite bands which typically occur a few metres from the base of the Marmorilik Formation, but which are always separated from the sediments by granodiorite. Locally, fine-grained biotite granite sheets, up to tens of metres thick, cut through the granodiorite; these are most common south-east of the 470 m lake and may reach, but are always cut by, the sedimentary contact. East of Qaumarujuk the basal contact does not outcrop; the Qaumarujûp sermikavsâ (glacier) and Quaternary deposits separate the marbles from a homogeneous biotite gneiss to the north.

The basal Quartzite-Semipelite Member

The basal clastic sedimentary sequence is fairly uniform throughout the area with a thickness from ca. 30 to 60 m. The unconformity is autochthonous, but local thrusting along the contact occurs west of the 746 m lake and on the northern margin of the open syncline. Typically a white orthoquartzite, few m thick, at the base of the formation is followed by impure, grey to green-brown quartzite with calc-silicates, local magnetite-rich quartzite (heavy sand), and semipelite grading into impure dolomite marble. Sedimentary structures (mainly wave ripple marks and cross-bedding) were occasionally found in the basal Quartzite-Semipelite Member; higher up in the formation primary structures are absent.

At type section 1

In the type locality described by HENDERSON & PULVERTAFT (1967) at the 915 m top ca. 1500 m south-west of the 480 m lake (U.T.M. 497600, 7886500), ca. 20 cm thick beds of white orthoquartzite with ripple marked surfaces form the lowermost 1–1.5 m of the formation. The ripple marks apparently are little deformed; they are symmetrical (oscillation ripples), the wavelengths are ca. 10 cm and amplitudes 2–3 cm, direction approximately NW–SE (Figure 3). The next 12 m comprise white and grey, 10–20 cm thick gravelly quartzite beds followed by greenish grey quartz-tremolite beds, with common cross bedding (foresets and bottom sets) which indicate right way up. The quartzites contain a little pyrite. These rocks are followed by a 1.5 m thick, buff (flesh pink weathering) dolomite bed with tremolite, phlogopite and pyrite, 6–8 m of impure rusty quartzite with lensoid semipelite intercalations on a metre scale and, near the top, with dm-sized tremolite-rich lenses. A second metre-thick buff dolomite bed is succeeded by a fine-grained flaggy semipelite rock, ca. 15 cm thick, with mm to few cm thick laminae in various grey colours.

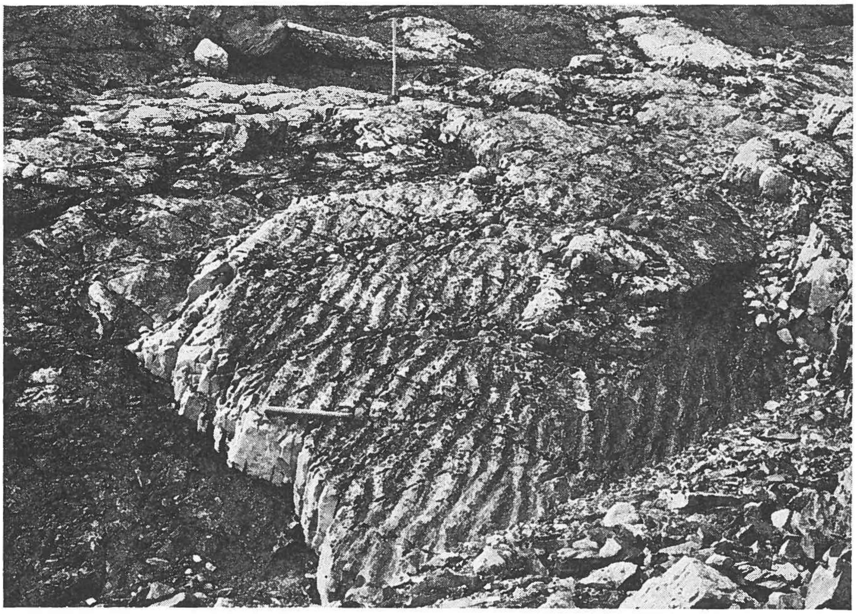


Fig. 3. The basal unconformity of the Marmorilik Formation (left). Pale ripple-marked orthoquartzite, lying direclty on granodiorite (dark). At the 915 m top.

The upper boundary of the Quartzite-Semipelite Member is transitional into impure dolomite marbles and consists of a 3–4 m thick sequence of mixed, 10–20 cm thick beds of dark, fine-grained semipelite, impure brown-grey laminated dolomite marble, and almost monomineralic green tremolite(-quartz-calcite) rocks with 2–5 cm thick quartz lenses fringed by tremolite.

South of the 480 m lake

The same sequence as along the type section is retained eastwards with minor modifications. The basal orthoquartzite with occasional ripple marks is followed by impure cross-bedded quartzites with calc-silicates and semipelite. West of the 470 m lake the semipelite is thin or absent.

South of the 480 m lake (U.T.M. 498750, 7886200) the Quartzite-Semipelite Member consists of 7 m orthoquartzite, ca. 3 m of impure quartzite with dm-sized bands rich in pale green tremolite, a ca. 2 m thick, brown weathering, iron-rich dolomite bed with tremolite and brown phlogopite, and ca. 12 m of cm-dm-banded black and grey quartzite and semipelite with several, up to a few cm thick, magnetite-rich beds that are believed to represent heavy sands, some of which were followed in the field up to ca. 100 m along strike.

West of the 746 m lake

1100 m west of the 746 m lake two types of conglomerate were found. One type, occurring in pockets 1 m and 5 m above the basal unconformity, consists of up to 10 cm large quartzite pebbles set in a gravelly quartzite matrix. The other type, which is seen ca. 15 m above the unconformity, is a 3–4 m thick, deformed partly intra-formational conglomerate. This conglomerate rests on a 2 m thick rusty semipelite bed with several, ca. 1 cm thick magnetite-rich layers. The components in the conglomerate are: ovoid (non-deformed) 2–10 cm long quartz pebbles, quartz gravel, light grey deformed semipelite cobbles up to 2 cm thick, 5 cm wide and 40 cm long, and cm-sized dolomite flags; the matrix consists of mainly quartz and brown mica with some carbonate, in which cm-sized tremolite porphyroblasts are locally developed. Near this locality ripple marks with varying ripple directions are common within 1 m from the basal unconformity, and graded bedding was noted in foresets of cross-bedded quartzites.

Petrography in the Quartzite-Semipelite Member

Quartzite, GGU 164407, type section 1 at the 915 m top, 5 m above the basal unconformity.

The rock is homogeneous and grey and is composed of polygonal quartz grains with undulose extinction and finely sutured grain boundaries; most grains are ca. 0.2 mm large but the grain size varies from 0.05 to 1 mm. A few sericitised microcline grains ca. 0.2 mm large occur. Interstitial colourless mica makes up 1–2 % of the rock and is seen as scattered clusters of minute flakes. Tourmaline (?), pyrite and secondary calcite and chlorite are rare accessories.

Greyish green calcite-phlogopite-quartz-tremolite knotenschiefer, GGU 164402, 1.4 km south-east of the bottom of Agfardlikavsâ (U.T.M. 493880, 7888500).

Ovoid, pale green, cm-sized rosettes of fine, radiating tremolite needles form approximately 50 % of the rock and are set in a matrix of quartz, calcite and pale apple-green phlogopite mica (determined with the electron microprobe); the mica forms closely spaced parallel trains of ca. 0.2 mm long flakes in the granular quartz and calcite with grain sizes of 0.1–0.3 mm. Calcite also occurs interstitially in the radiating tremolite aggregates.

Semipelite, GGU 164413, type section 1, 150 m east of the 915 m top.

The hand sample is fine-grained and exhibits a sequence of grey siliceous and brown-grey biotite-rich (?sedimentary) layers on a cm-scale. Under the microscope the grey layers (80–90 % of the rock) are seen to consist mainly of quartz, with some microcline and biotite, with grain sizes around 0.05×0.1 mm, all with a pronounced preferred orientation. The brown-grey layers and lenses are made up mainly of biotite, with some polygonal quartz and microcline, grain sizes around 0.2 mm. A weak foliation at ca. 45° to the bedding is formed by 0.1–0.2 mm wide zones of pure biotite.

Magnetite-rich clastic rock, GGU 164433, south of the 480 m lake, 30 m north-east of the base of the formation (U.T.M. 498790, 7886220).

A polished section of a specimen from a magnetite-rich rock contains equal amounts of magnetite and silicates, and rare ilmenite and pyrite. The section covers two graded beds, 0.5 and 1 cm thick, of strongly corroded and fractured magnetite crystals with occasional ilmenite rims, and with sizes ranging from ca. 0.1–1 mm, in recrystallised finer-grained biotite, quartz and microcline. Within each bed the magnetite is almost massive in the lower part and more scattered higher up, with a general decrease in size upwards. The beds are thought to be metamorphosed heavy sands.

Impure magnetite-biotite-banded quartzite, GGU 164432, same locality as no. 164433.

The sample has a sedimentary banding on a mm–cm-scale with varying grain size and colour. Under the microscope massive bands of polygonal quartz with interstitial randomly orientated biotite grains are the most common; each quartz grain is around 0.1 mm large and frequently has minute opaque inclusions in its centre. In addition there are thin bands rich in corroded magnetite, biotite and/or dolomite. Pale green tremolite-actinolite needles up to 1 cm long are occasionally present.

Impure tremolite-bearing dolomite marble, GGU 164411, type section 1, 80 m north-east of the 915 m top (from a 1 m thick, flesh pink weathering dolomite marble bed).

In thin section this marble is mainly granular dolomite; the weakly elongate grains are 0.1–0.2 mm long. Many 0.01–0.05 mm large euhedral pyrite grains are scattered in the dolomite. Tremolite occurs in zones a few mm thick at intervals of 2–5 cm, as single colourless to pale green prisms a couple of mm thick, often surrounded by fine-grained calcite-phlogopite intergrowths; the tremolite is poikiloblastic with frequent rounded 0.02–0.05 mm large calcite inclusions. Quartz occasionally occurs as irregular, corroded single grains intergrown with tremolite or bounded by tremolite and calcite, but is not seen in mutual contact with dolomite.

The Lower Dolomite Member

A complete list of the members of the Marmorilik Formation is given in Plate 6 together with a generalised stratigraphic column. The marbles fall into two groups, a lower consisting (mainly) of various types of dolomite marble and an upper dominated by calcite marble.

The Lower Dolomite Member, which follows the basal Quartzite-Semipelite Member, has an estimated predeformation thickness of ca. 700 m. It comprises (from the lower boundary upwards) impure siliceous, often tremolite-bearing dolomite marble with a distinct compositional bedding on a scale of metres to tens of metres (Plate 2a), followed by massive, pure, light and dark grey dolomite marble, locally also dark grey banded calcite-dolomite marble. Near the top of the member there are several 5–10 m thick dolomite marble beds containing up to ca. 30 % quartz. The Lower Dolomite Member contains two distinct semipelite beds, ca. 4 and 8 m thick, as well as several thinner units of only local extent.

At type section 1

The transitional contact in the type area between the Quartzite-Semipelite Member and the Lower Dolomite Member has already been described. Above the transition zone the ca. 200 m thick sequence of planar, little deformed dolomite marble units (Plate 2a) below the first semipelite bed is as follows: ca. 20 m of greenish grey tremolite- and phlogopite-rich dolomite marble with ca. 30 cm long quartz lenses in the lowermost 5 m; light-coloured dolomite with minor phlogopite and pyrite; medium grey dolomite marble, often banded with cm-sized tremolite crystals; a distinct 10–15 m thick impure dark grey dolomite marble unit with tremolite, phlogopite and accessory scapolite and pyrite. Above this tremolite disappears, and quartz-rich dolomite dominates, the marble being intercalated with 0.5–5 cm thick quartz lenses with grain sizes of ca. 0.1–0.2 mm.

Dolomites from the lower part of the Lower Dolomite Member have calcite contents ranging from 1–9 wt. % of the total carbonate and hydrochloric acid insoluble residues from 3–25 % — typically ca. 10 %.

Above the quartz-rich dolomite follows the first distinct semipelite bed in the marble (visible in both fault blocks in Plate 2a); this is 4–5 m thick and black-grey with rusty brown weathered surfaces. The rock is fine-grained with mm-sized laminae, and is crossed by joints in two directions at right angles, both perpendicular to the bedding, at ca. 10–30 cm intervals. The semipelite is more quartzitic than that at the lower boundary of the Lower Dolomite Member, and graphite is an essential component.

West of the 470 m lake

The rocks around the 710 m tops make up roughly the same succession as in the type area; the semipelite cropping out from the 470 m lake westwards is the second semipelite of the Lower Dolomite Member. Layers several m thick rich in tremolite are prominent in this area. A detailed stratigraphy is difficult to establish due to low-angle thrusts and isoclinal folds (Figure 12) with horizontal axes. Folding and thrusting has led to repetition of part of the sequence above the thrust plane shown on the map (Plate 7), but apparently without increasing its total thickness (see the cross-section h–h, Plate 6). On the cliff-side facing south, west of the 470 m lake, several semipelite bands are seen which are almost certainly one and the same bed.

At type section 2 (south-east of the 480 m lake)

In the area between the two large lakes the lower part of the Lower Dolomite Member is much the same as at the 915 m top; the most complete stratigraphic section occurs on the ENE–WSW-trending ridge 1–1.5 km south-east of the 480 m lake (type section 2). Here the lowermost part of the member is cut off by faults just below the first semipelite horizon, and the second semipelite horizon is sheared out and repeated along several local thrusts (which are not shown on the map); evidence of isoclinal folding was not found here.

Homogeneous, fine-grained, light dolomite marble like that between the two semipelites continues ca. 50 m above the second semipelite up to a characteristic sharp, often wavy boundary to the overlying ca. 15 m thick, dark grey marble rich in minute graphite flakes (seen in the microscope to be distributed along grain boundaries); in this unit homogeneous dark grey dolomite at the base gradually changes into dark grey dolomite-calcite marble banded on a cm–dm-scale (locally with pure grey calcite marble) which is succeeded by a ca. 5 m thick dolomite marble bed with conspicuous layers with several cm wide stellate tremolite aggregates, talc, and scattered randomly orientated 1–2 cm long pseudomorphs of scapolite prisms.

The homogeneous dolomite marbles, with or without graphite, have a low calcite content, less than 5 $^0/_0$ of total carbonate, and insoluble residues around 10–15 $^0/_0$, whereas the tremolite-rich variety has up to 15 $^0/_0$ calcite as a result of metamorphic reactions. The banded two-carbonate rocks may contain up to 50 $^0/_0$ calcite.

The 200 m thick sequence overlying the tremolite-scapolite dolomite is variable: quartz-rich dolomites replace tremolite-bearing rocks, and there are several red-brown weathering beds 1–3 m thick which have compositions from impure quartzite to semipelite, and quartz-dolomite-phlogopite rock with irregular bands at a cm–dm-scale. Pure dolomite marble also occurs.

The upper boundary of the Lower Dolomite Member is a thrust zone separating light dolomite marble from the Thin Calcite Marble Member above; the thrust zone consists of yellow to brown, 10 to 30 cm thick bands of marble with cm-sized semipelite bands and lenses.

Between the 480 and 746 m lakes

An incomplete succession of the Lower Dolomite Member can be traced towards the east along a NW–SE-trending tight syncline, the north-eastern flank of which is flattened, in places inverted and bounded to the north-east at two different stratigraphic levels by thrust planes. Along these thrusts quartz-rich dolomite marble is converted into several metres of white talc-calcite schist with pale green to pink tints. In the hinge zone of the western end of the fold pseudomorphs, presumably of scapolite, are well developed in the dolomite marble; they have prismatic outlines, are up to $^1/_2$ cm thick and several cm long and protrude in all directions on weathered surfaces, also in minor fold closures. Above the thrusts quartz-rich dolomite marbles with thin rusty semipelite bands are followed by a ca. 40 m thick, uniform and pure, light grey dolomite marble, in which a 1–2 m thick, massive light grey chert or dense quartzite band was followed 1.5 km along strike. This rock occasionally contains dark grey bands and streaks a couple of cm thick.

The Lower Dolomite Member terminates with a 5–10 m thick bed of impure, dark yellow dolomite marble. The upper contact is almost everywhere tectonic (a thrust).

Petrography in the Lower Dolomite Member

Dolomite marble with tremolite, phlogopite and calcite, GGU 164415, the lower part of the Lower Dolomite Member, type section 1 325 m east-north-east of the 915 m top.

The hand specimen is a light grey dolomite marble with frequent layers of stellate tremolite aggregates, white to pale green, a centimetre or two thick. In thin section the dolomite has a granular texture; the grains are untwinned and unusually large, up to ca. 0.3 mm. Colourless phlogopite plates, 0.1–0.2 mm large, are scattered in the dolomite. The individual tremolite crystals in the rosettes vary in thickness from a few microns to 0.3 mm, and the rosettes contain interstitial calcite.

Impure dolomite marble, GGU 164408, locality near no. 164415; from the distinct dark grey dolomite marble unit near the base of the formation.

The sample has an indistinct foliation of alternating dolomite and ca. 5 mm thick silicate-rich lenses at 2–3 cm intervals; in these lenses 5–10 mm large poikiloblastic tremolite crystals, pale brown phlogopite mica and up to 10 mm long scapolite prisms are set in a matrix of granoblastic, ca. 0.1 mm large dolomite and ca. 1 mm large (secondary) calcite grains (Figure 8). The massive, fine-grained dolomite layers have a granoblastic-elongate texture, a rather uniform grain size of ca. 0.1 mm, and are rich in interstitial graphite flakes a few microns long. Rutile and pyrite are accessory. Secondary veins of white calcite and dolomite occasionally contain anhedral, interstitial sphalerite grains up to 0.5 mm large.

Semipelite, GGU 164417, type section 1; the lowest semipelite band in the Lower Dolomite Member.

The semipelite is mainly composed of quartz with subordinate albite, pale brown mica and graphite, and has an indistinct and irregular lamination on a mm-scale defined by grain size variations, the degree of preferred orientation of the silicates, and variations in composition. Quartz and feldspar show a granoblastic weakly to strongly elongate texture, with grain sizes ranging from 0.01–0.5 mm in mm-thick seams without distinct boundaries. Mica plates with size similar to that of quartz and albite, and minute graphite specks and flakes, are interstitial in various amounts.

Grey dolomite marble, GGU 164424, with prismatic pseudomorphs, south-east of the 480 lake, U.T.M. 501400, 7887240 (above the second semipelite of the Lower Dolomite Member).

The hand specimen is massive, very fine-grained and dark grey with few white patches of recrystallised carbonates, 2–5 mm large. Under the microscope the rock consists of unusually fine-grained, granular dolomite (grain size less than 0.1 mm) with a weak preferred orientation. The grey colour of the specimen is due to the presence of disseminated graphite in and between dolomite grains. As is typical for many dolomite marbles this sample contains scattered single grains, ca. 0.1 mm large, of pale phlogopite, subhedral albite and quartz, as well as euhedral pyrite (0.1–0.2 mm); the silicates show a tendency to be concentrated in zones parallel to the foliation in the carbonate. Quartz also forms rare, up to 1 mm large clusters of anhedral grains. A pseudomorph, presumably of scapolite with a nearly square cross-section 2 mm wide, is intergrown calcite and albite (centre) surrounded by chlorite (rim).

Dolomite marble with tremolite, calcite and talc, GGU 164443, type section 2 at the 845 m top.

The hand sample is grey, fine-grained dolomite marble with scattered, several cm large white rosettes of tremolite prisms surrounded by thin silky talc covers less than one mm thick. The weathered rock is porous and crumbling. The tremolite crystals in thin section are corroded and separated from the massive, granular dolomite by intergrowths of talc plates ca. 0.5 mm long and calcite (Figure 9). Scattered talc grains also occur in the dolomite.

Dense quartzite, GGU 164521, 200 m east of the 866 m top between the 480 and 746 m lakes (U.T.M. 502780, 7887060), from a 1 m thick band.

Under the microscope (polished thin section) the dense quartzite or chert consists of minute quartz grains with elongate ovoid outlines and sizes of 0.005–0.02 mm; as the grain size is larger than 35 microns the rock is not a real chert according to McBride & Thomson (1970). The dark bands occasionally present are due to dark, rounded specks of unknown composition, a couple of microns large, which are concentrated in irregular streaks at ca. 0.1 mm intervals in the dark areas. Anhedral to subhedral pyrite (smaller than 0.1 mm), pyrrhotite and secondary limonite are the most common accessories. Single grains of carbonate, colourless mica, microcline, rutile (rounded), and sphene (idiomorphic), all with sizes under 0.1 mm, were also seen, whereas no graphite was found. The accessories found here are all common in marbles as well.

The Thin Calcite Marble Member

The Thin Calcite Marble Member consists of calcite marble bounded by brown, banded calcite(-dolomite)-semipelite rocks; its maximum stratigraphic thickness is ca. 50 m. The member has been traced more than 7 km along strike from the 746 m lake in the east to the western end of the 470 m lake where it thins out and disappears. A few m thick impure, dark yellow calcite marble bed occurs on the 348 m hill south-east of Agfardlikavsâ above a thrust and probably represents the Thin Calcite Marble Member.

At type section 2 the calcite marble is light yellow, fine- to medium-grained, phlogopite-bearing, and contains ca. 10–20 % fine-grained dolomite aggregated into flat, ca. 0.5 times 1.5 cm thick rods that protrude on weathered surfaces and have a dark yellow colour due to a higher iron content than the calcite. The same rock forms the top of the 856 m high, characteristic ridge 1 km west of the 746 m lake (U.T.M. 502600, 7887120).

South of the 480 m lake the Thin Calcite Marble Member is thrust over dark grey dolomite-calcite marble beds of the Lower Dolomite Member and is repeated by isoclinal folds.

The Grey Dolomite Member

Massive, homogeneous, medium to dark grey, phlogopite-, pyrite- and often graphite-bearing dolomite marble with occasional zinc- and/or lead mineralisations is the highest stratigraphic unit preserved between the 480 m and 746 m lakes, and it also forms the plateau at ca. 550 m elevation north of the 470 m lake. In both areas two semipelite beds are present. The unit has an estimated stratigraphic thickness of minimum ca. 325 m. The marble typically contains between 4 and 10 % calcite and only little acid insoluble material, often down to 2–3 %.

At type section 2 and between the 480 and 746 m lakes

The preserved sequence of the Grey Dolomite Member in the area south-east of the 480 m lake is ca. 350–400 m thick measured on the thicker, southern flank of the main syncline; its lower boundary is placed at the top on the uppermost brown carbonate-semipelite bed of the Thin Calcite Marble Member. The dolomite marble is typically massive and fine-grained, light to medium grey and almost pure dolomite with accessory phlogopite, feldspar, pyrite, and often graphite. To the east in the core of the syncline the marble is schistose and weathers into 1–3 cm thick flags; elsewhere the foliation is often obliterated by a penetrative lineation.

In the marble there are two continuous semipelite bands, a lower of ca. 5 m and an upper of 5–20 m thickness, as well as a couple of 4–8 m thick dolomite horizons with 20–40 % quartz concentrated into bands, lenses or rods a couple of cm thick alternating with dolomite. The dolomite up to a few metres above each semipelite band is slightly enriched in iron and weathers buff to yellow. Pyrite is common in the marble, and occasional sphalerite (-galena)-bearing veins were found (see p. 55).

At type section 3 north of the 470 m lake

The Grey Dolomite Member west of the 480 m lake is a lateral continuation of the rocks described so far, and also here contains occasional mineralised veins. Passing upwards along type section 3 (following section E–F on the map, plate 7, northwards from the 470 m lake), the member becomes progressively more schistose and dark grey in colour north of the second semipelite band. The marbles here resemble those along type section 2 but have a more distinct granoblastic elongate texture and larger grain sizes (up to ca. 0.3 mm); locally they contain small amounts of sphalerite and/or galena.

Above the grey dolomite occurs a 1–4 m thick layer of light grey, orange-brown weathering, pyrite-rich dolomite marble.

Petrography in the Grey Dolomite Member

Grey dolomite marble, GGU 164440, 450 m east of the eastern end of the 480 m lake; a typical specimen of the Grey Dolomite Member sampled between the two semipelites.

The hand sample is massive, dark grey, fine-grained dolomite. Streaks and lenses, 1–5 mm thick, of white mm-grained dolomite and calcite, and occasional thin layers of pale buff phlogopite form a weak foliation. Under the microscope the granular dolomite has a weak preferred orientation, with fine graphite as inclusions and on grain boundaries. Pseudomorphs of scapolite are seen in the microscope as patches composed of very fine-grained colourless mica, carbonates, and albite. Other accessories are phlogopite, albite, calcite, pyrite, and rare 0.01 mm large molybdenite flakes (identified in reflected light) in graphite-rich areas. A secondary veinlet of mm-grained, granular, clear dolomite flecked with mica crosses the thin section; the neighbouring dolomite is unusually rich in graphite. The sample contains ca. 5 % calcite and only 2 % insoluble residues.

Inverted sequences and tectonic breccia at type section 3

The upper boundary of the Grey Dolomite Member outcrops 500–700 m north of the 470 m lake and is a thrust zone striking E–W, dipping N, along the lower flank of a recumbent, tight to isoclinal fold. Its closure is visible 100 m north-west of the 480 m lake; the fold involves rocks belonging to the Banded Marble and Massive Calcite Marble Members (see pp. 20–21).

Passing upwards from the Grey Dolomite Member one encounters a many metres thick, dark brown weathering tectonic breccia consisting of dark grey lensoid semipelite fragments (size ca. 0.5–1.2 cm) separated by ca. 1 mm thick envelopes of buff calcite, and of scattered cm-dm-sized wavy semipelite layers with thin calcite-filled cracks; the breccia is followed by a ca. 20 m thick buff, massive calcite unit; both units belong to the Massive Calcite Marble Member and are wrong way up (see p. 21).

The Banded Marble Member

The Banded Marble Member at type section 3 (along the slope between the two plateaus at ca. 550 and 700 m elevations) has a present total thickness of ca. 250 m; most of the member consists, from the bottom upwards, of dolomite marble with m-thick pale horizons of "chert" or dense quartzite, pure grey and dark grey dolomite marble, a characteristic ash-grey unit up to over 100 m thick with a calcite-dolomite banding on a scale varying from centimetres to metres, and yellow quartz-rich dolomite marble. The ash-grey unit is bounded by semipelite-rich bands and can be followed laterally from the fold nose north-west of the 480 m lake westwards for more than 6 km into the fjord Agfardlikavsâ.

The (right way up) boundary between the Banded Marble and the Massive Calcite Marble Members, where quartz-rich dolomite marble changes into massive calcite marble, can be located to within a few m along the southern edge of the calcite marble plateau at 650–750 m elevation; the quartz-bearing dolomite, which is more resistant to physical and chemical weathering than calcite, forms the steep slope down from the plateau. Sometimes the boundary is the site of a dense, pale grey to yellow, 1–2 m thick "chert" band, as in the fold closure northwest of the 480 m lake.

Petrography in the Banded Marble Member

Dolomite-calcite-semipelite-banded marble, GGU 164465, 1.1 km north of the 470 m lake near type section 3 (U.T.M. 496380, 7889850), from the ash-grey unit.

The hand sample is dark, fine-grained dolomite with mm- to cm-sized tight folds and streaks composed of semipelite and mixtures of semipelite, calcite and dolomite. The rock weathers dark brown. Mm-grained white calcite occurs as patches in fold closures and elsewhere, often together with phlogopite. The same types of layers are found in thin section: a) granoblastic-polygonal dolomite, grain size ca. 0.1 mm, with interstitial quartz, phlogopite, graphite, pyrite and pyrrhotite (partly or wholly oxidised to limonite), b) granoblastic-elongate quartz-albite-microcline-phlogopite-carbonate (grain size from 0.03–0.1 mm) with interstitial graphite, often forming tight fold closures with mimetic mica flakes on their outsides, c) secondary granular calcite (-dolomite-phlogopite-quartz). One 0.01 mm large chalcopyrite inclusion was found in pyrrhotite.

Dense quartz-mica rock, GGU 164464, type section 3 950 m north of the 470 m lake (U.T.M. 497300, 7889670).

Under the microscope the sample consists mainly of quartz together with pale brown mica (?phlogopite) and occasional albite and microcline, all with grain sizes of ca. 0.05 mm. A banding parallel to the general bedding is visible as slight variations in grain size and mica content on a scale of mm to cm. The texture of the quartz (which forms 80–90 % of the rock), is granoblastic-elongate; the quartz orientation together with the preferred orientation of evenly dispersed mica flakes defines a foliation not visible in the hand specimen, at ca. 50° to the compositional banding. The sample contains rare cm-sized recrystallised spots with rounded boundaries, of granular quartz and microcline, grain size 0.1–1 mm.

The Massive Calcite Marble Member

The stratigraphy of the interval with a present thickness of ca. 700 m, sometimes more, between the Banded Marble Member and the Semipelite Member is not completely understood; the whole sequence is termed the Massive Calcite Marble Member, massive calcite being the dominant rock type.

There are also buff to white quartz-bearing dolomite marbles, and banded calcite-dolomite marbles including dark varieties with semipelite and/or quartz bands (Plate 2b). On the map (Plate 7) full blue and green colours are used to indicate where calcite or dolomite predominates, but these rocks may be regarded as local modifications of the same lithologic unit(s).

The massive, phlogopite-bearing calcite marble resembles that of the Thin Calcite Marble Member; the dolomite content varies from nil to ca. 20 %, and quartz and albite are minor constituents, occurring as scattered mm-sized aggregates of equidimensional grains; fresh scapolite was occasionally noted. Grey calcite marbles are graphite-bearing and as in the dolomites the graphite occurs as minute flakes along grain boundaries. The insoluble residues typically form around 5 % of the rocks, but 10–20 m thick sequences of calcite marble with no dolomite and less than 2 % insoluble material are known. The compositions of marbles from the Massive Calcite Marble and other Members in terms of calcite, dolomite and insoluble residue are shown in Figure 2.

The bedding commonly seen in dolomite marble is not found in the calcite marble, but secondary structures such as phlogopite lineations and dolomite rods or dm-sized folds are very common.

At type section 3

Yellow calcite marble on the plateau continues up the slope from ca. 800 to 1000 m elevation, where isoclinally folded, 25–75 m thick, flat-lying bands of brown, semipelite-banded calcite(-dolomite) marble and white dolomite marble with quartz are seen (for example around U.T.M. 486500, 7890800); the quartz, forming 10–30 % of the rock, occurs as irregular cm–dm-sized lenses, rods and patches in zones at intervals of cm to a few dm (see Figure 5). The white quartz-bearing dolomite marble is recognised from a distance by colour and by vertical joint systems.

North of the 480 m lake

A less deformed variety of the spotted breccia described on p. 20 occurs north-west of the northern end of the 480 m lake (around U.T.M. 498600, 7890000). Above this, massive dark yellow calcite marble is traversed by numerous semipelitic bands varying in thickness from a few cm to a few m; these bands are generally parallel, but often isoclinally folded and sometimes boudinaged (Figure 4). The same rock-type forms the E–W-trending, folded band 500 m north of the lake. At close quarters hinge zones of internal folds are characteristic by their well-developed dolomite and semipelite rods in a calcite matrix; bedding planes and foliations cannot be followed around the closures. The unit is found again at the plateau at 800 m elevation north-east of the 480 m lake (around U.T.M. 500800, 7890100), and further north and north-west of the ice-dammed 760 m lake. In this area the rocks are less deformed; there are well-defined, ca. 25 m thick white, yellow and grey-brown layers of calcite-dolomite marble with regular 0.5–1 m thick semipelite beds.

The banded rocks are overlain by 250 m of massive calcite marble followed by an allochthonous unit of light yellow to white quartz-rich dolomite with quartz contents around 20 %, that resembles that at type section 3. In this dolomite several tight folds were mapped, using 5–10 m thick brown semipelite-quartz-carbonate bands as structural markers (Figure 14). Also massive calcite marble is folded into this unit. A sheet of massive, white and grey medium-grained calcite marble above a second thrust zone is the highest structural (and probably stratigraphic) unit of the Massive Calcite Marble Member found here; this is covered by moraine to the north. Near the 1008 m top a ca. 15 m thick unit in the light calcite marble is formed of flaggy, dark grey graphite-rich calcite marble, rusty impure quartzite bands a few dm thick and dark yellow dolomite marble.

Petrography in the Massive Calcite Marble Member

Pale buff calcite marble, GGU 164461, 900 m north-west of the 480 m lake (U.T.M. 497450, 7889960).

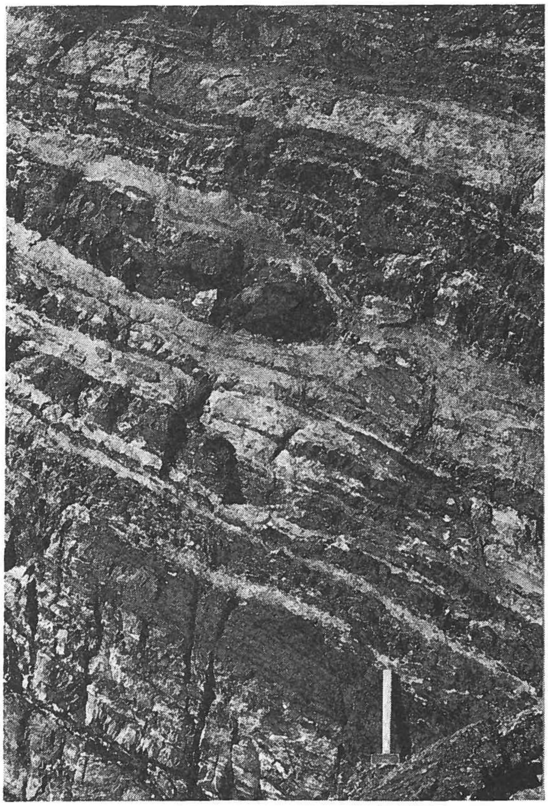


Fig. 4. Irregular, sometimes boudinaged semipelite bands in calcite marble 250 m north of the northern border of the 480 m lake.

The hand specimen is a typical massive calcite marble with flat, 1–2 mm thick rods rich in brown phlogopite. Under the microscope the calcite is granoblastic-granular to elongate; the grains vary in size up to 2 mm and are generally twinned. Single crystals of phlogopite, quartz and albite, 0.1–0.2 mm large, are frequently found in corners between calcite grains; massive aggregates of phlogopite, albite and dolomite (grain sizes 0.05–0.2 mm) form the rodding mentioned above. Pyrite and rutile are rare accessories.

Dark grey calcite marble, GGU 164468, 1.4 km north of the 480 m lake (U.T.M. 499200, 7891250).

The hand sample is massive ash-grey calcite-graphite marble, grain size 1–2 mm; the rock is flaggy, and a distinct foliation of the calcite is visible. In thin section the sample consists of elongate calcite grains with a preferred orientation; the larger crystals are fractured and consist of domains 0.1–0.3 mm large with slightly varying optical orientations. Grain boundaries are very irregular. Small amounts of quartz, potassium feldspar and muscovite occur as scattered anhedral grains 0.1–0.3 mm large; dolomite is not present. Graphite is very common as massive, irregular, up to ca. 0.05 mm thick seams parallel to the foliation, and is also found as small inclusions both in calcite and silicates.

Streaked calcite marble, GGU 164473, 1 km north-west of the 480 m lake (U.T.M. 498250, 7890630).

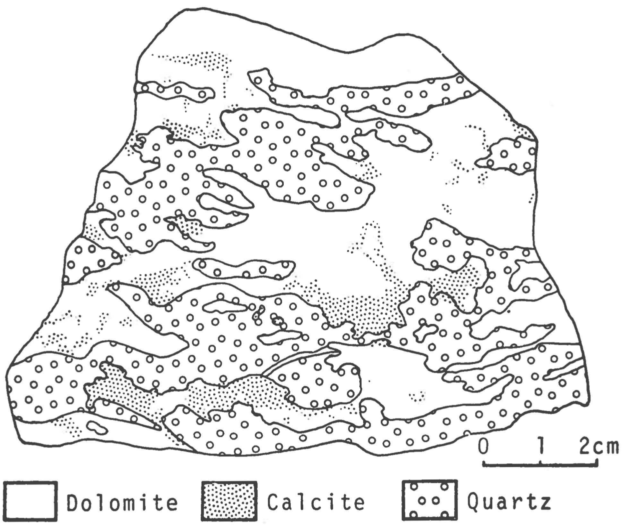


Fig. 5. Slice of siliceous dolomite marble showing irregular patches and bands of massive quartz and associated calcite in the matrix dolomite (GGU 164476).

The hand specimen is fine- to medium-grained calcite marble, irregularly streaked on a mm to cm scale in light and dark grey colours. Under the microscope the rock is largely composed of 1–2 mm large, equidimensional, strongly twinned calcite crystals which are separated from each other by a fine-grained meshwork of mainly calcite, some quartz and minor muscovite and potassium feldspar (grain sizes ca. 0.1 mm). Clusters of graphite specks are scattered in the fine-grained meshwork, sometimes associated with ca. 0.1 mm large subhedral pyrite grains with secondary rims of limonite.

Grey mica-banded siliceous dolomite marble, GGU 164471, 600 m north-west of the 480 m lake (U.T.M. 498630, 7890420), from a quartz- and semipelite-banded unit.

The marble is brownish grey and fine-grained, with up to 1 mm thick phlogopite bands and streaks at intervals of mm to cm. The thin section contains dolomite, calcite, quartz, albite, phlogopite, and pyrite; approximately equal amounts of dolomite and quartz together form over 90 % of the rock. The granular dolomite (-calcite), grain size 0.1–0.3 mm, contains clusters and lenses a few mm large of a) quartz with interstitial dolomite, grain size 0.05–0.2 mm, and b) quartz-albite(-dolomite) with grain size around 0.03 mm; these quartz- and quartz-albite aggregates may be remnants of original separate laminae. The mica-rich bands are each composed of several trains of pale brown phlogopite flakes up to 0.5 mm long, set in a matrix of granular dolomite(-calcite).

White quartz-rich dolomite marble, GGU 164476 (U.T.M. 495900, 7890650); a typical specimen (loose block) from a ca. 50 m thick dolomite band in the cliff near the northern end of type section 3.

The rock is composed of fine-grained dolomite with accessory silicates, mainly quartz, and pyrite, and 1–2 cm thick zones of massive, glassy quartz as well as mm-grained calcite patches, interlobing with the dolomite (Figure 5). Quartz occurs both as massive, pure quartz (seen in thin section to consist of very irregular 0.1–0.4 mm large recrystallised grains with wavy interlocking boundaries and undulose extinction), and also in patchy aggregates up to ca. 3 mm large in the fine-grained dolomite; besides quartz the aggregates contain albite, phlogopite and dolomite as equidimensional grains ca. 0.05 mm large.

Fig. 6. Graphite-rich semipelite, see p. 26, (ab) albite, (bi) biotite, (gr) graphite, (qtz) quartz. Plane polarised light (GGU 164450).

The Semipelite Member (Black Angel mountain)

As mentioned before the upper stratigraphic boundary of the Marmorilik Formation is not known. The highest unit found is the at least ca. 200 m thick Semipelite Member which occurs on the top of the Black Angel mountain in the area considered here (partly covered by Quaternary deposits and ice).

The lower boundary of the Semipelite Member is often a zone of displacement, e.g. 1.6 km north-east of the bottom of Agfardlikavsâ where the movement of a large ENE–WSW-trending normal fault with downthrow to the west is partially taken up along the boundary between marble and semipelite; at other localities marble and semipelite are folded into tight, angular folds on a scale of ca. 10 m, or the boundary is a chaotic mixture of brecciated marble and semipelite. However, in many places there is a gradual transition from marble to semipelite in situ. Generally the position of the semipelite is near to horizontal, with open to tight folds at the boundary to the marble, and there is a weak WNW–ESE-trending foliation at an angle varying from 50–90° to the flat-lying bedding.

The semipelite is dark grey with rusty, dark brown weathering colours, fine-grained and usually less fissile than the lower semipelite bands in the marble; it is mainly composed of quartz, some albite and biotite, and there are also small amounts of very fine-grained (?)epidote and, locally, carbonates. Both pyrite and, particularly towards the north and west, pyrrhotite are locally common, and near the contact to the marbles the semipelite is often very rich in graphite, which is concentrated in thin seams together with biotite (Figure 6). The semipelite is always dark, fine-grained and rather uniform in the field, but there are considerable local variations in composition, texture and grain size (see the sample descriptions below).

Petrography in the Semipelite Member

Graphite-bearing semipelite, GGU 164450, Black Angel mountain 250 m south-west of the 1128 m top, at the base of the Semipelite Member (U.T.M. 493220, 7891270).

The hand sample is black-grey, very fine-grained and has a uniform lamination of mm-thick bands in varying dark grey shades, separated by very thin biotite bands. Irregular specks of pyrrhotite up to 1 mm large are locally seen. The rock is set through by angular folds with amplitudes of ca. $^1/_2$ cm and axial planes perpendicular to the general bedding. In thin section the dark grey laminae are composed of mainly albite (identified with the microprobe), quartz, and minor biotite, with grain sizes around 0.02 mm and a granoblastic-granular texture. Numerous graphite flakes and specks are present along the silicate grain boundaries. The quartzofeldspatic laminae are separated by up to 0.2 mm thick bands of biotite and almost massive graphite. The biotite grains are up to 0.05 mm long and have preferred orientations both parallel to the lamination and to the axial planes of the microfolds (Figure 6).

Massive dark grey semipelite, GGU 164467, north of the 480 m lake, 320 m north-east of the 1074 m top (U.T.M. 498830, 7891570).

The hand sample is massive and fine-grained with a weak silky sheen. Under the microscope the rock consists of an imperfectly schistose aggregate of elongate anhedral quartz and albite grains and biotite laths, grain sizes being 0.05–0.1 mm. Frequent 0.1–0.2 mm large ovoid albite and quartz porphyroblasts are set in the finer matrix. Fine graphite is everywhere present and often forms almost massive, up to 0.03 mm thick rims around the larger quartz and albite grains (Figure 7).

The north face of the Black Angel mountain

The stratigraphy which has been established on the southern flank of the large syncline cannot be followed directly to the north face of the Black Angel mountain because of the structural complications which are visible on the cliff face opposite Mârmorilik (Figure 16). Nevertheless the sequence on the north face, visited north-east of the tributary glacier on

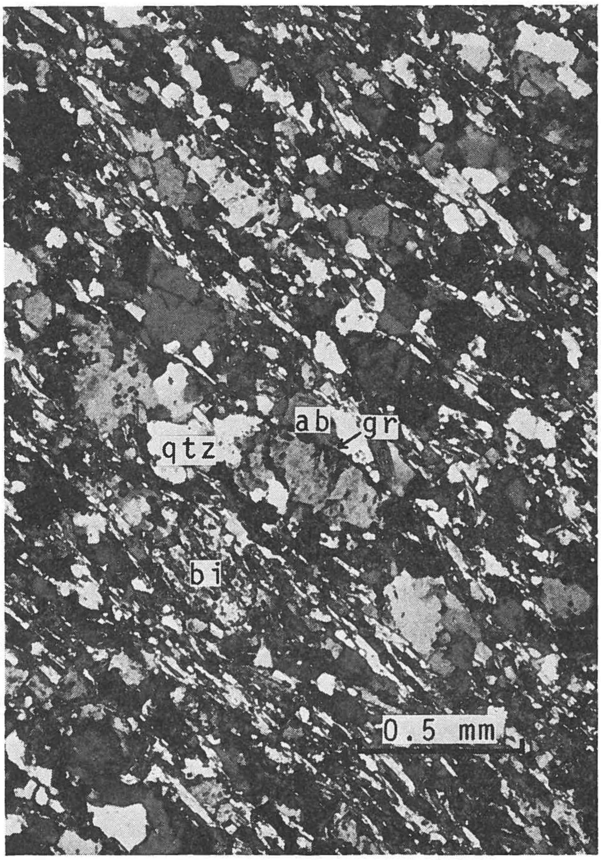


Fig. 7. Semipelite, see p. 26, abbreviations as for Figure 6. Crossed nicols (GGU 164467).

the north face of the mountain, is to a large extent comparable to the one described so far, and a tentative correlation has therefore been carried out.

The lowest sequence seen consists of various dolomite marbles belonging to the Lower Dolomite and Grey Dolomite Members, which have an outcropping thickness of 300 m and include at least two semipelite horizons; these dolomites are followed by 100 m of banded, grey dolomite-calcite marble of the Banded Marble Member, and ca. 200 m of chaotic, faulted and brecciated mixtures of yellow, quartz-bearing dolomite marble and light yellow calcite marble (the Banded Marble and Massive Calcite Marble Members); these rocks are shown as undifferentiated marble north-east of the tributary glacier. Then follow 300 m of mainly grey, massive, medium-grained calcite marble with several 10–20 m thick semipelite and dolomite bands, all belonging to the Massive Calcite Marble Member and folded into a large "S" (viewed towards south-west), see Figure 17. At 600 m elevation below the fold (south-west of the tributary glacier) a sulphide mineralisation crops out in the shape of a ca. 50 m long band; if the interpretation of the north face stratigraphy is correct, this mineralisation lies in the Banded Marble Member.

The marbles are overlain by the Semipelite Member.

Dolerite dykes

Three dolerite dykes cut through the area: one from the bottom of Agfardlikavsâ in the direction SE–NW (thickness 80 m), a second north of the 470 and 480 m lakes, direction ENE–WSW (thickness ca. 20 m), and a third north-east of the eastern end of the 746 m lake, direction swinging from N–S to NW–SE (thickness ca. 50 m).

The dykes have fine-grained, but not really chilled, margins where these are exposed, and primary ophitic textures in their centres; they are generally deeply weathered and crumbling. The dykes postdate both deformation and metamorphism. The second dyke has sent m-thick apophyses into calcite marble, and north of the 480 m lake it is locally split into several thinner dykes.

Quaternary deposits

The Precambrian bedrock is generally very well exposed; except for scattered boulders and sparse soil Quaternary deposits are largely restricted to screes at the foot of steeper slopes, and local stone fields. Small areas with a thin cover of moraine occur between the 480 and 746 m lakes, and the Inland Ice is generally bounded by a many metres high moraine. Quaternary deposits have not been differentiated on the map.

III. METAMORPHISM

Introduction; field observations

Mineral parageneses in siliceous dolomite marbles in the area east of Mârmorilik indicate a regional metamorphic grade in the Marmorilik Formation corresponding to the greenschist facies. In the field the abundant occurrence of tremolite in the lowermost part of the formation is the most obvious effect of metamorphism; massive lenses of quartz in the dolomite are here surrounded by tremolite rosettes up to several cm thick. The present thickness of the basal zone in which tremolite is repeatedly found is at most ca. 300 m, thickest in the western part of the area; higher up tremolite is absent except for the local occurrence of tremolite-bearing dolomite (-calcite) marble beds a few metres thick. These rare tremolite occurrences have no obvious relations to their

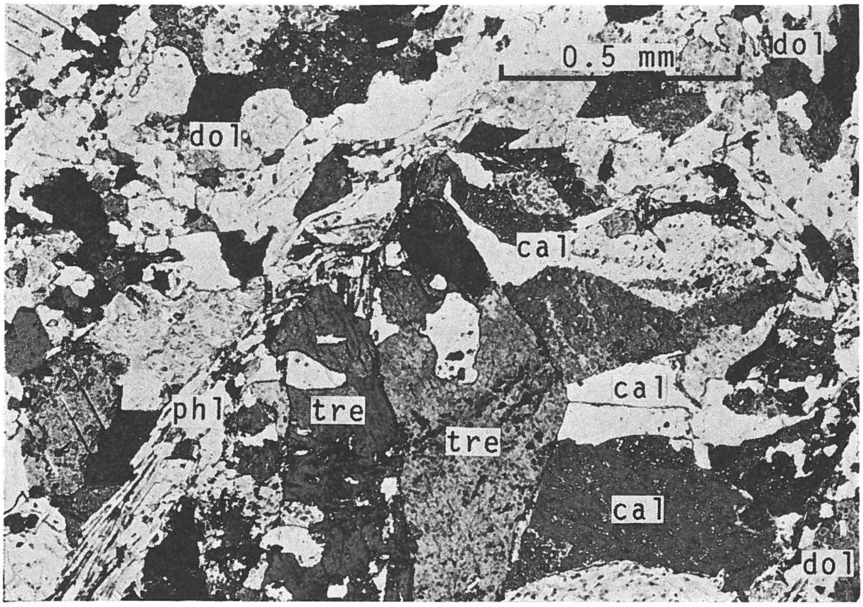


Fig. 8. Tremolite prism surrounded by columnar calcite in a siliceous dolomite marble, (cal) calcite, (dol) dolomite, (phl) phlogopite, (tre) tremolite. Crossed nicols (GGU 164408).

stratigraphic or structural positions. Diopside was only seen at one locality within the mapped area, a few metres above the basal unconformity, but massive diopside is known to occur at Tasiussaq, 6 km west of the end of Agfardlikavsâ (T. C. R. PULVERTAFT, pers. comm.). Pale brown to colourless mica, later identified with the microprobe as phlogopite, was observed in all parts of the formation, in both calcite and dolomite marble. Scapolite was sporadically found both near the base of the formation in dolomite marble and near the top in calcite marble. However, pseudomorphs up to several cm long and with square cross-sections, which are thought to be after scapolite, are locally common in all parts of the formation. These pseudomorphs now consist of fine-grained intergrowths of albite, quartz and calcite, rimmed by chlorite. Talc in the parageneses dolomite-calcite-talc and calcite-tremolite-talc was only found in one sample of ordinary marble (GGU 164443 from type-section 2 south-east of the 480 m lake); generally talc is restricted to obviously retrograde occurrences in late veins and in talc-calcite (-dolomite) schists and breccias along faults.

From the field observations it thus appears that there is a slight decrease in the metamorphic grade upwards and eastwards in the formation, and that local retrogression has occurred.

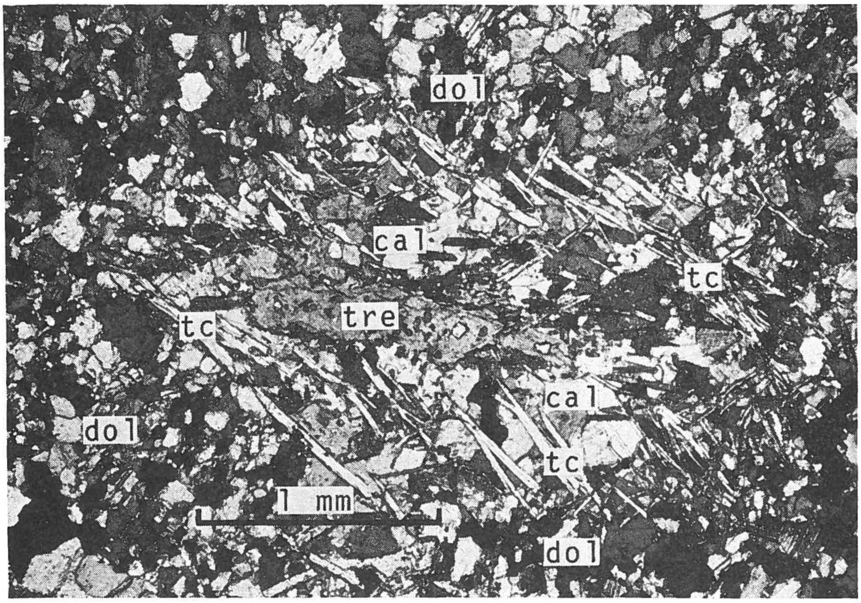


Fig. 9. Corroded tremolite prism, separated from the fine-grained dolomite by calcite and talc. The orientation of the retrograde talc flakes is at an angle to the general foliation, (cal) calcite, (dol) dolomite, (tc) talc, (tre) tremolite. Crossed nicols (GGU 164444).

Mineral parageneses

Under the microscope the following stable mineral parageneses were found in the marbles and calc-silicate rocks (as indicated by minerals found in contact with each other):

In dolomite marble, generally with less than 10 % calcite:

dolomite-calcite-quartz-phlogopite ± albite ± K-feldspar
dolomite-calcite-tremolite-phlogopite ± albite ± K-feldspar
dolomite-calcite-tremolite
dolomite-calcite-talc and calcite-tremolite-talc

In calcite marble:

calcite-quartz-phlogopite ± dolomite ± albite ± K-feldspar
calcite-quartz-muscovite ± albite ± K-feldspar
calcite-quartz-muscovite-biotite-albite-K-feldspar
calcite-quartz-tremolite-phlogopite ± albite
calcite-quartz-diopside

(in the marbles silicate accessories other than feldspars are scapolite, sphene, and chlorite, as well as secondary talc and serpentine). In the semipelites quartz, albite, biotite ± K-feldspar ± muscovite ± (?) epidote occur.

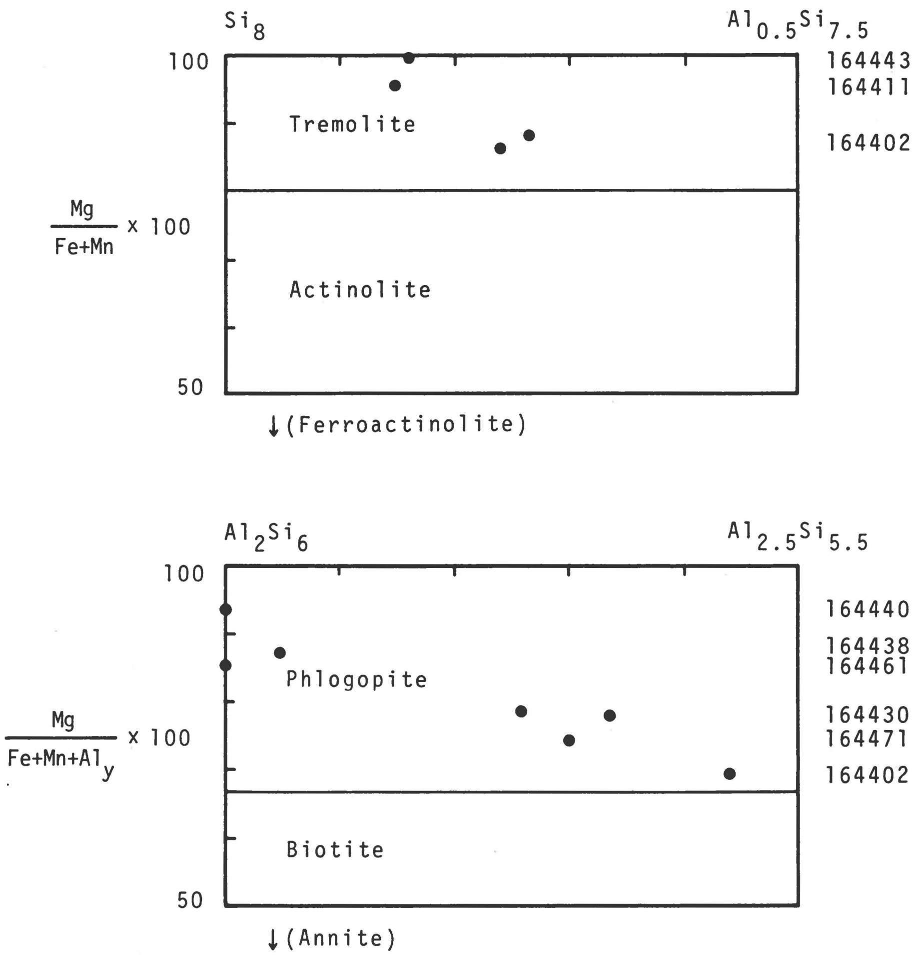


Fig. 10. Mg, Fe+Mn, Al, and Si contents of tremolites and phlogopites from various marbles and calc-silicate rocks (GGU numbers right). All iron as Fe^{2+}. The nomenclature follows DEER *et al.* (1970).

Tremolite is invariably intergrown with or surrounded by calcite (Figure 8), and several tremolite-bearing specimens contain both dolomite and quartz, but not in mutual contact; in these rocks tremolite sometimes forms single crystals around a core of quartz, or aggregates with calcite separating quartz from dolomite, the distance between dolomite and quartz being generally less than one cm. In the talc-bearing sample GGU 164443 tremolite and dolomite are separated from each other by talc and calcite, indicating that talc is a reaction product of the former two minerals (Figure 9).

Mineral compositions

In addition to a large number of carbonate analyses (see below), microprobe analyses of phlogopite and tremolite were carried out in a few samples. The results are shown in Figure 10. The compositions need little comment, being nearly pure tremolite and phlogopite end members as expected in siliceous carbonates low in iron (see for example RICE, 1977). Phlogopite contains slightly more iron than coexisting tremolite; the more iron-rich varieties of both minerals were found in impure calcite-dolomite marbles and calc-silicate rocks with colours in green and brown shades near the base of the formation. Talc in sample GGU 164443 mentioned above has the approximate composition

$K,Na,Ca_{0.01}Mg_{5.9}Fe_{0.1}Al_{0.02}Si_{7.93}O_{20}(OH)_4$.

Coexisting muscovite and biotite in GGU 164456, a semipelite-banded calcite marble from the Banded Marble Member, have the compositions

$K_{1.88}Na_{0.07}Ca_{0.04}Mg_{0.34}Fe_{0.24}Mn_{0.04}Ti_{0.09}Al_{3.41}Al_{1.81}Si_{6.19}O_{20}(OH)_4$

and

$K_{1.83}Na_{0.03}Ca_{0.03}Mg_{3.29}Fe_{1.70}Mn_{0.01}Ti_{0.23}Al_{0.53}Al_{2.43}Si_{5.57}O_{20}(OH)_4$.

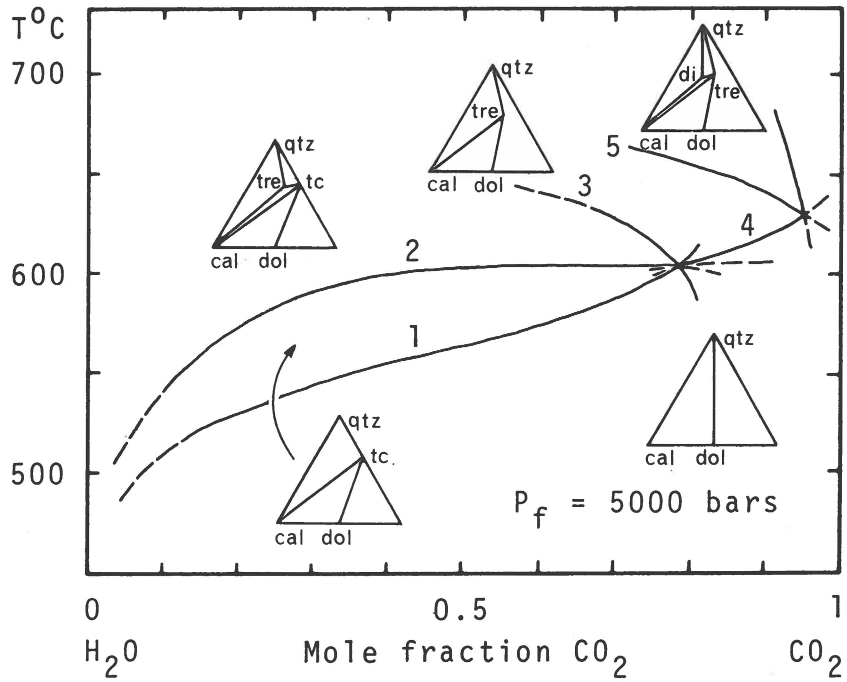
A zoned scapolite from a calcite marble (GGU 164460) varies from Me_{27} in the centre to Me_{38} in the ca. 0.2 mm thick rim and contains 2.6 % chlorine, but no sulphur.

The analyses were performed with the Hitachi XMA-5B Scanning Electron Microprobe at fixed selected points, and using natural minerals as standards. The details of analytical procedure were as described in GARDE (1977).

Carbonates from 19 samples were analysed for Ca, Mg and Fe with the microprobe in order to determine the temperature of metamorphism by means of the calcite-dolomite solvus geothermometer. The results of this investigation (GARDE, 1977) do not lend themselves to any interpretation in terms of metamorphic temperature, because variations in composition of calcites within single samples are much larger than the total variation of the averages, and the inferred trend, if any, of the metamorphic gradient is the opposite of that observed in the field.

Conditions of metamorphism

The following discussion is an attempt to classify the metamorphic conditions during metamorphism of the Marmorilik Formation in terms of temperature-pressure-mole fraction CO_2. Although exact figures would be desirable — in particular for an evaluation of ore-concentrating processes — only estimates can be given on the basis of present knowledge:



$$(1)\ 3dol + 4qtz + 1H_2O \rightleftharpoons 1tc + 3cal + 3CO_2$$
$$(2)\ 5tc + 6cal + 4qtz \rightleftharpoons 1tre + 6CO_2 + 2H_2O$$
$$(3)\ 2tc + 3cal + 1tre \rightleftharpoons 1dol + 1CO_2 + 1H_2O$$
$$(4)\ 5dol + 8qtz + 1H_2O \rightleftharpoons 1tre + 3cal + 7H_2O$$
$$(5)\ 1tre + 3cal + 2qtz \rightleftharpoons 5di + 3CO_2 + 1H_2O$$

Fig. 11. Equilibrium curves of reactions in siliceous carbonates with compositions between pure calcite, dolomite and quartz for temperature versus mole fraction CO_2 at a total fluid pressure of 5000 bars. (cal) calcite, (di) diopside, (dol) dolomite, (qtz) quartz, (tc) talc, (tre) tremolite. Compiled from PUHAN & HOFFER (1973) and WINKLER (1974).

calcite-dolomite thermometry is inconclusive, and no diagnostic mineral parageneses were found.

Work in the field and, recently, in the laboratory (TILLEY, 1948; PUHAN & HOFFER, 1973; TROMMSDORFF, 1972; SUZUKI, 1977) has demonstrated that talc is to be expected in progressively metamorphosed siliceous dolomites before the occurrence of tremolite. Talc may be formed by reaction between dolomite, quartz and water (reaction no. 1, Figure 11); only at high ratios of CO_2 to H_2O is tremolite formed directly from dolomite and quartz. As stated by WINKLER (1974, p. 114) talc is not produced if a high X_{CO_2} has already been generated, for example by the

K-feldspar + dolomite + H_2O = phlogopite + calcite + CO_2 reaction (this reaction has been studied experimentally by PUHAN & JOHANNES, 1974). In the Marmorilik Formation phlogopite, and not talc, is generally found, which implies that the X_{CO_2} was high at the peak of metamorphism. Probably the production of phlogopite in most cases consumed all available K-feldspar, as albite is frequently the only feldspar found in the marbles; the microprobe proved a convenient tool in identification of 0.01–0.1 mm large feldspar grains embedded in carbonate.

The very sporadic occurrence of tremolite in the carbonate members above the basal tremolite-rich sequences, in spite of the widespread occurrence of rocks of suitable composition, can be explained by a general weak decrease in temperature and pressure upwards through the succession, combined with local increases in the water content of the marbles which allowed sporadic formation of tremolite by reaction 4 (Figure 11). At still higher water contents the equilibrium curve of reaction 3 (Figure 11) is met, as illustrated by sample no. GU 164443, where talc has been formed at the expense of tremolite and dolomite. Several geologists have reported the not uncommon appearance of isobaric univariant parageneses in metamorphosed siliceous marbles, i.e. parageneses containing both reactants and products of a given reaction in equilibrium, and have demonstrated that in such cases the composition of the H_2O–CO_2 phase is buffered by the reactions. In some cases also isobarically invariant parageneses were demonstrated, and the metamorphic temperature thereby determined for a given pressure. In the Marmorilik Formation isobaric univariant parageneses have not so far been found.

The maximum metamorphic temperature attained in the area under consideration is reflected by the occurrence of diopside, found in a single locality. However, the formation of diopside (e.g. by reaction 5, Figure 11) is much dependent of the total fluid pressure: at 2000 bars diopside may be formed at temperatures down to ca. 510°C (SKIPPEN, 1971), but at 5000 bars not under ca. 640°C (WINKLER, 1974, p. 120).

An estimate of the minimum lithostatic pressure at the base of the Marmorilik Formation may be obtained from evidence that the Nukavsak Formation of the Karrat group once extended far outside its present limits — probably also over the Marmorilik Formation (ESCHER & PULVERTAFT, 1976). Five km of overburden from the Nukavsak Formation plus 2 km from the Marmorilik Formation itself corresponds to a lithostatic pressure of ca. 2000 bars at the base of the formation; this is regarded as the minimum figure, whereas a pressure of 5000 bars is probably too high (it may be mentioned that wollastonite has been found on the island of Agpat 30 km south-west of Mârmorilik (R. A. GANNICOTT, pers. comm.), indicating metamorphism under a low CO_2-pressure).

In summary, the metamorphism of the Marmorilik Formation east of Mârmorilik has taken place in the presence of a CO_2-rich volatile phase, resulting in the typical parageneses dolomite-calcite-quartz-phlogopite and dolomite-calcite-tremolite-phlogopite, at temperatures of up to 500°C (accepting a total volatile pressure around 2000–3000 bars), and with local retrogressions in the presence of more water. Also the coexisting albite and biotite in the semipelites point towards metamorphism of greenschist facies grade.

Timing of metamorphism

Syntectonic growth of phlogopite, quartz and dolomite is commonly evidenced in rodding and mineral lineations, but metamorphism has outlasted the main phases of folding and thrusting. The carbonates have readily recrystallised until a late stage of deformation; strained, strongly twinned calcite and dolomite may however be found near thrusts. Both tremolite, fresh scapolite and their pseudomorphs are generally randomly orientated; there are good examples of random scapolite growth in minor fold closures near the hinge zone of the tight syncline west of the 746 m lake, whereas tremolite occurs in places where the rocks are generally little deformed. However another indication that the metamorphism outlasted the major structural events is found at the 348 m hill east of Agfardlikavsâ, where marbles from higher stratigraphic levels have been brought near to the granodiorite contact. Like everywhere else near the base of the formation, these rocks are rich in tremolite, which formed after the thrusting which carried the rocks in question to their present position.

IV. STRUCTURE

General structure

The large open syncline

The Marmorilik Formation east of Mârmorilik has a general E–W to NW–SE strike and has the gross structure of an open syncline with an approximately ESE–WNW, nearly horizontal axis; in the western end of the area the axis plunges to the west. The southern flank of the syncline is exposed all through the southern part of the area; it generally dips 25–35° N to NE. In the central part of the fold where rocks belonging to high stratigraphic levels occur, dips rarely exceed 20° N. The northern margin of the syncline is only exposed in a small ice-free area 2 km north of the 746 m lake, but part of the northern flank also appears east of

Qaumarujup qíngua, where the base of the formation is concealed by Quaternary deposits (see p. 27).

Since it is the base of the formation, and not the top, that is exposed along the northern margin, the large recumbent anticline originally depicted by HENDERSON & PULVERTAFT (1967) is not substantiated, neither in this area nor ca. 15 km further west at Magdlak (GARDE & PULVERTAFT, 1976).

In the eastern part of the syncline where its northern margin crops out, a series of some 700 m of dolomite marble below the upper part of the Grey Dolomite Member is missing on the northern flank; the semipelite which is exposed between the 603 and 702 m lakes is the second semipelite of the Grey Dolomite Member, as is seen in the area 600–800 m east of the north-eastern end of the 480 m lake (U.T.M. 7889000, 500900), where the flat-lying semipelite occurs on both flanks of the open hinge zone of the syncline. The strong asymmetry of the fold, compared to the usually large lateral extent of the sedimentary strata, is explained as a consequence of thrusting that has cut off part of the succession on the northern flank; a definite plane of thrusting was not found in the field, but possibly some of the movement has taken place along the semipelite as indicated on the cross-sections A–B and C–D, Plate 7.

Faults

The outcrop pattern of the formation is influenced by a number of steep, N–S to E–W-trending faults, many of which are curved (convex to the E) and have sinistral displacements. In the field the faults occur as up to several metres wide zones of crushed rocks, and in marble dolomite is sometimes almost completely replaced by calcite. Talc is also commonly found. Frequently the lateral slip is absorbed gradually northwards in the marble.

There are also normal faults with downthrow to the W, e.g. on the cliff-side north-east of Agfardlikavsâ.

Recumbent folds and thrusts

Tight to isoclinal recumbent folds are common throughout the mapped area above the basal part of the formation. The recumbent folds are often accompanied by low-angle thrusts, only the more important of which have been shown of the map (Plate 7). The folds generally have nearly horizontal axes which coincide with that of the open syncline and with rodding and mineral lineations (see Plate 4 and below), but there are exceptions to this rule (p. 48). Planar elements are often obliterated in the closures of the folds, which are characterised instead by strong rodding (see below). The fold closures face both N (to NE) and S (to SW), also within one and the same small area.

Fig. 12. Isoclinal fold closures in dolomite marble — note the second closure pointed at (450 m south-west of the border of the 470 m lake, looking east towards the Inland Ice).

The recumbent folds tend to be concentrated in certain stratigraphic zones, and are most frequent in the western and upper parts of the formation, which have also suffered the strongest degree of deformation. In the area west of the 470 m lake there are many recumbent folds with E–W-trending axes in the middle part of the Lower Dolomite Member; their isoclinal closures were found both in semipelite beds and in marble (Figure 12), commonly along the front of the E–W-striking thrust plane, indicating that the folding and thrusting are related. The fold closures face both N and S; the extent of each fold could not however be mapped in the massive dolomite marble.

In the fault blocks further east, tight to isoclinal folding and thrusting have taken place in the upper part of the Lower Dolomite Member and in the Thin Calcite Marble Member, e.g. south of the 480 m lake. Here the Thin Calcite Marble Member rests on dark dolomite-calcite marble of the Lower Dolomite Member with a thrust discordance above which there are several tight folds, often with thrust movements along their limbs (Figure 13).

The highest stratigraphic levels of marble along the cliff-faces north and west of the lakes are more strongly deformed than the lower parts of the formation. Recumbent isoclinal folds with axes trending E–W to NW–SE and plunging from ca. 20° WNW to 10° ESE, combined with

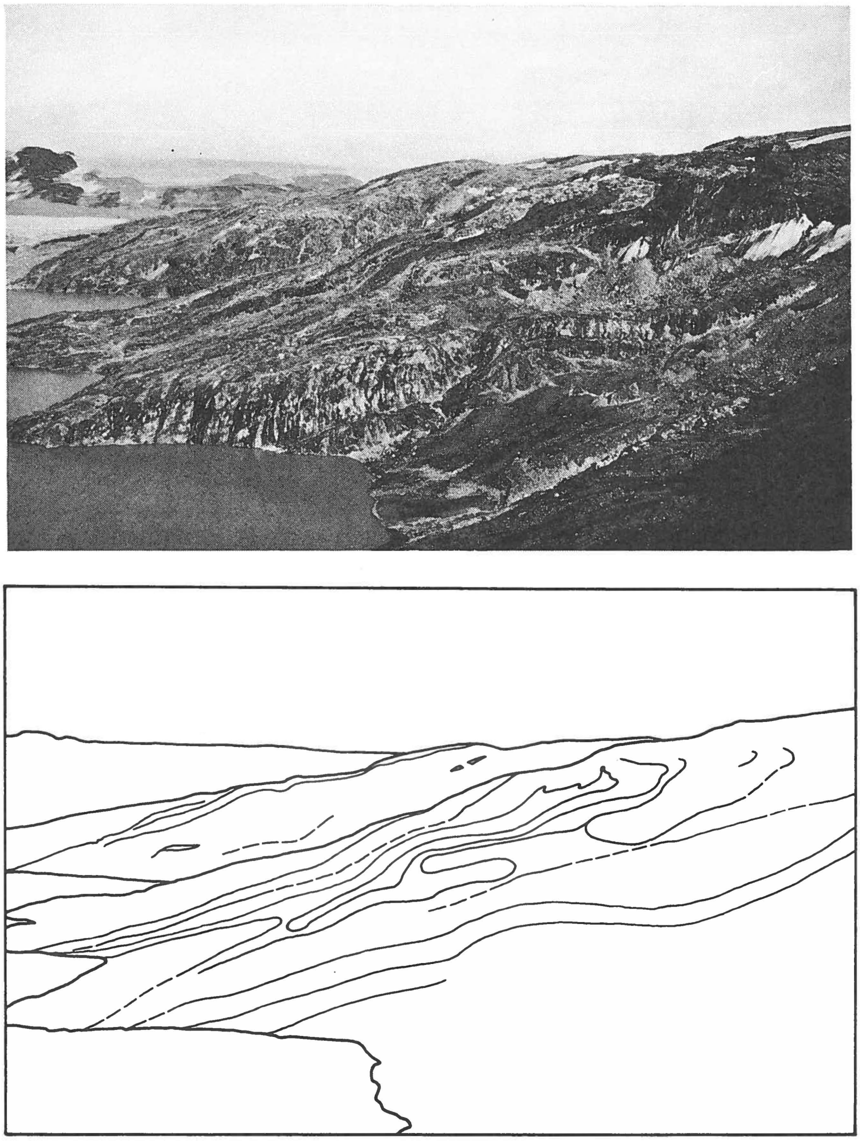


Fig. 13a–b. Isoclinal folding and thrusting in the Lower Dolomite and Thin Calcite Marble Members (view from helicopter towards the east of slopes south of the 480 m lake).

zones of intense disturbance due to overthrusting, are essential elements of the structure in this area. The folds have not been proved to affect more than ca. 150 m predeformation thickness. As the cliff-faces in most of the area are approximately parallel to the fold axes, the outlines of the folds seem more extreme than is actually the case.

In the area north of the 480 m lake the fold axes diverge from the

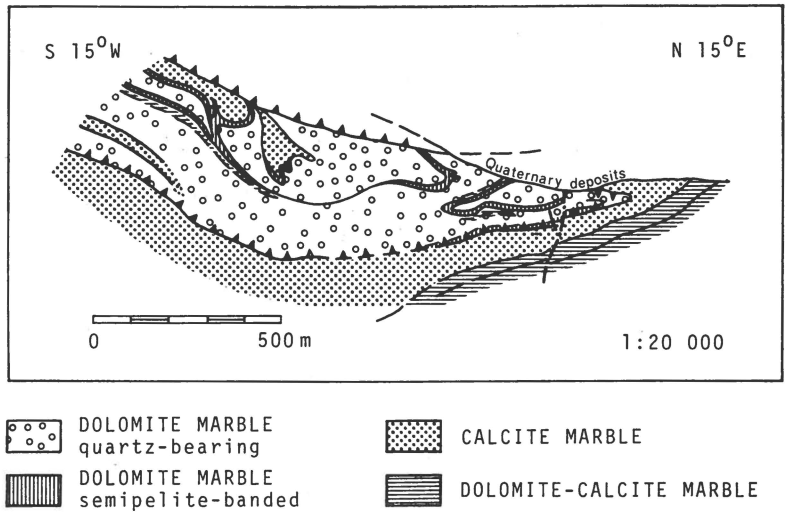


Fig. 14. Profile 0.7–2 km north of the northern border of the 480 m lake; folds and thrusts in calcite and quartz-rich dolomite marble. The structures have been projected along an average fold axis 285/20 onto a plane orientated 15/70 E.

topographic relief, and a profile perpendicular to fold axes has been constructed (Figure 14) to illustrate the general style of deformation occurring in alternating calcite- and dolomite-quartz rocks at this structural level. The folds were traced out in the field using light brown markers, a few m thick, of iron-rich dolomite interbanded with semipelite. The interaction between folding and thrusting is well illustrated: the lower thrust is folded into an isoclinal closure, whereas the upper one transsects several folds. Fold closures also here face both N and S, and several of them have digitate fronts. The area seems to owe its general synformal shape to the large open syncline; if so, the syncline refolds both the recumbent folds and the thrusts.

The recumbent fold north-west of the 480 m lake has already been mentioned on p. 20; it is a good example of a marble fold in which planar elements are not preserved near the closure. The quartz-rich dolomites and banded calcite-dolomite marbles found in ca. 950 m elevation along the cliff-faces north of the two lakes have been assigned to the Massive Calcite Marble Member (see p. 21), and assumed to be right way up. If, however, the fold just mentioned was the lower closure in a large "S" (looking NW), the series in question could be an inverted repetition of part of the Banded Marble Member; in consequence the estimated stratigraphic thickness of the Massive Calcite Marble Member would be reduced from ca. 550 to 250–300 m. There is no direct evidence however of such a fold, and the dolomite rocks in the higher position are different from the lower ones, being more uniform, lighter coloured, and without the massive cherty bands characteristic of the Banded Marble Member. Therefore the interpretation involving the "S" is not favoured by the writer.

Open folds and monoclines

In the area there are several weak to open, rounded folds and monoclines on a scale of 50–500 m, which are seen on the dip-slopes south and west of the 470 and 480 m lakes (where they also affect the recumbent folds) as weak undulations of the marbles; in other areas they are recognised as local variations in the general dip, for example in the Grey Dolomite Member east of the 480 m lake.

Structures in restricted areas

A tight syncline between the 480 and 746 m lakes

Up to 2 km west of the 746 m lake occurs a tight, overturned fold with a WNW–ESE-trending hinge line changing from ca. 110/20 to 110-horizontal from west to east. The fold affects strata from the upper half of the Lower Dolomite Member — the same stratigraphic/tectonic level as is cut off by thrusting in the fault blocks south of the 480 m lake. The southern limb of the fold dips regularly some 35° NE; the northern limb is steep to vertical, towards the east overturned, and here the rocks are thinned, locally to a third to a quarter of their thickness on the southern limb. In the fold closure towards the west there are abrupt dip variations within a few metres in banded dolomite-calcite marble, whereas in the eastern end of the fold, layers of quartz-rich dolomite marble in the closure are more regular and flat-lying. Minor structures in the fold are described on p. 52.

To the north the boundary of the fold is marked by a thrust zone with moderate to steep northerly dip that is overlain by quartz-rich dolomite marble, the stratigraphic position of which corresponds to that of similar rocks in the hinge zone of the tight syncline. Distinct, steeply inclined S-dipping axial surface foliations continue north of the thrust boundary of the fold. To the east the fold is cut by a NE–SW-trending fault, which begins near the centre of the fold. Part of the southern fold limb continues eastwards with a northerly dip, but the rest of the fold cannot be traced across the fault: to the east, opposite the central part of the tight syncline, a small anticline is found, and the strata in a ca. 500 m wide zone north of the anticline are steeply inclined to vertical, and flaggy. Another 500 m further north the fault quietly dies out. Apparently the faulting has been active during the formation of the tight fold.

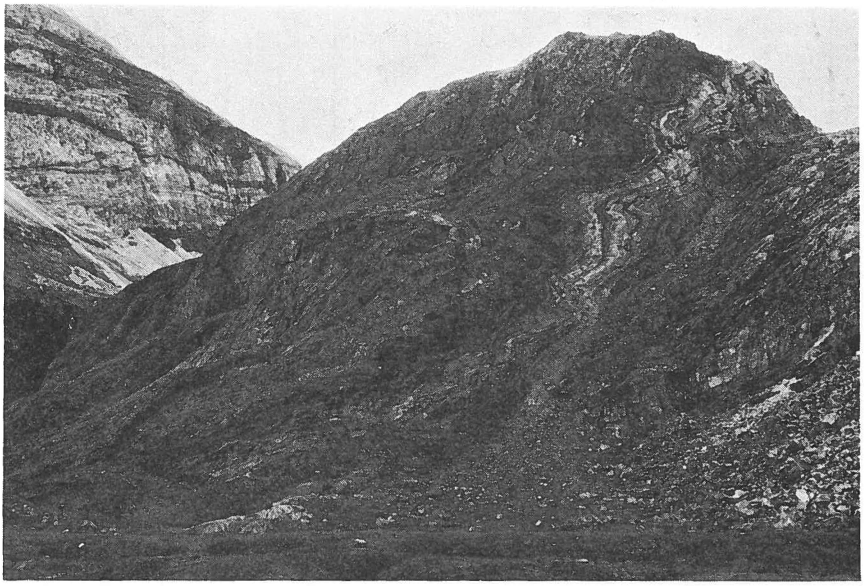


Fig. 15. NW-vergent folds on the 348 m high hill east of the bottom of Agfardlikavsâ. Mainly dolomite marble, with thin dark semipelite bands and a light band of calcite marble.

Angular folds east of Agfardlikavsâ

On the 348 m high hill east of Agfardlikavsâ a series of open to close, angular folds with NW vergence and amplitudes in the order of 10 m can be seen in semipelites overlying impure calcite and dolomite rocks (Figure 15). Minor folds in these folds are disharmonic, with very varying dips of axial surfaces, but without any signs of superimposed folding.

Structure of the Black Angel mountain

The structure of the Black Angel mountain is more complicated and not so well understood as in other parts of the area, and requires a treatment of its own. Much information about the Black Angel mountain was obtained by means of binoculars, as the cliff faces are for a large part inaccessible. Outcrops on the top of the mountain are of little value because the general structure is flat-lying; furthermore, it was often impossible to get reliable structural measurements on the top because the bedrock is broken up into loose flags, and proper outcrops are rare.

Structure of the cliff facing Agfardlikavsâ

North-west of the normal fault visible above the bottom of Agfardlikavsâ the cliff is divided into two structural units by an inferred thrust above yellow calcite marble, in a very high stratigraphic position (Figure

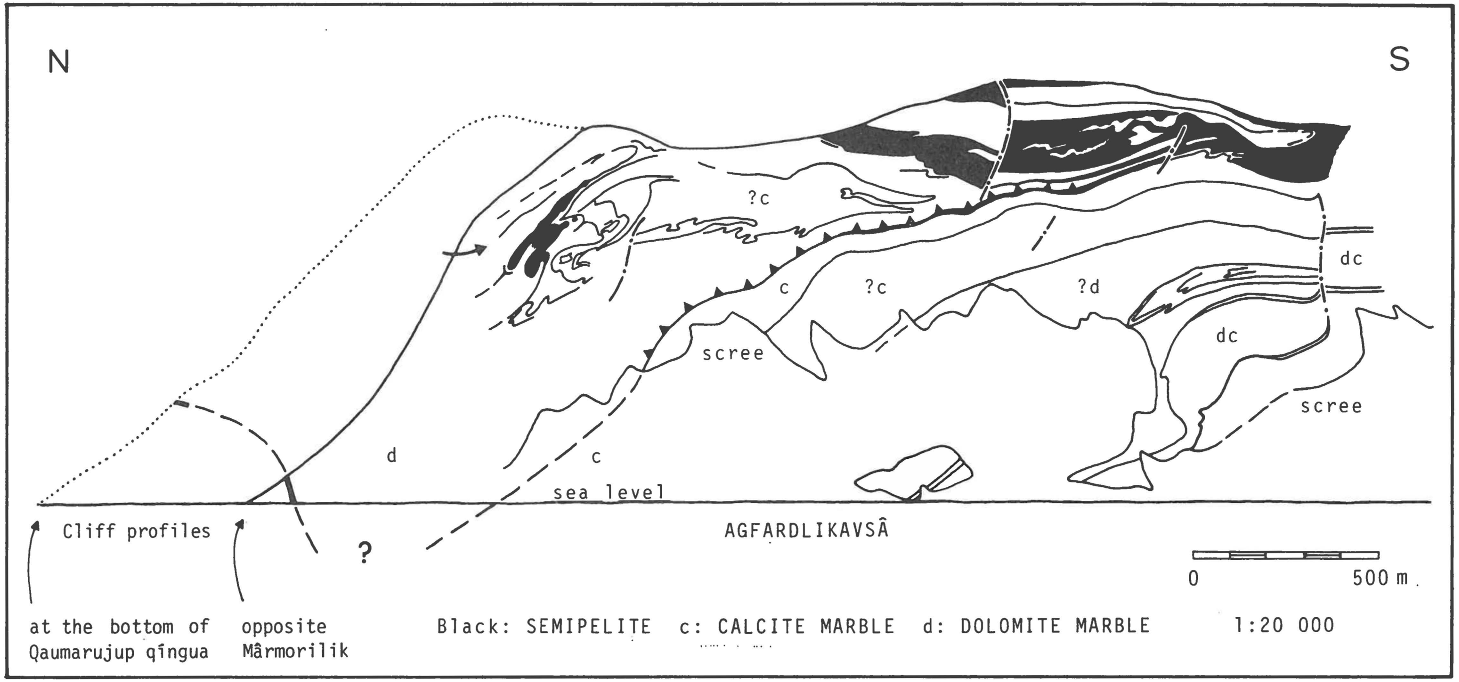


Fig. 16. Projection on a vertical N–S-striking plane of structures north-east of Agfardlikavsâ (projection plane approximately perpendicular to fold axes). Black: semipelite; blank: marble; at the arrow: outcrop of the "angel zone" ore body within the uppermost closure of the Black Angel semipelite. The figure is based on a computer-drawn projection from ca. 600 geological points, measured on oblique aerial photographs with a stecometer. The computer programme was developed by K. S. DUEHOLM.

16); above the bottom of the fjord this calcite marble is situated at 800 m altitude, while to the north-west it bends down to sea level under the angel, where the dip is ca. 50° N (this level can be correlated across to Mârmorilik mine-camp). The flat-lying semipelite above it remains near the top of the mountain. Under this thrust, part of the marble sequence is repeated by isoclinal folds facing N. Above the thrust, to the south-east, massive grey (presumably calcite) marble in 750–800 m elevation, and possibly the semipelite bounding it as well, is folded into a large recumbent, tight fold closing S with a double marble "nose".

The Black Angel area opposite Mârmorilik is separated from this fold by a steep fault, which is traceable from ca. 550–750 m altitude. The Black Angel itself is a semipelite band with six isoclinal closures facing alternatively N and S, probably formed during a single phase of deformation (axial trend approximately E–W and horizontal based on information from the mine inside the mountain). White, light grey and dark grey marbles near the Black Angel have been mobilised, as seen south-east of the semipelite closures. The ore body crops out as a narrow, ca. 200 m long, northward-dipping rusty band between the flanks of the uppermost S-closing fold of the semipelite; another outcrop of the ore is situated nearby at the cliff facing Qaumarujuk, where it forms a separate, ca. 300 m long band. Below the angel it is very difficult to discern any structures in the marble.

Structure of the north-west facing cliffs

The cliffs facing Qaumarujûp qíngua run approximately parallel to fold axes, and the most valuable information is therefore obtained where the tributary glacier has cut into the cliffs. The lower half of the visible succession is little affected by folding and dips regularly 20–30° SE; in the upper part a large "S" fold, outlined by a semipelite band, is seen when looking south-west across the tributary glacier (Figure 17). The semipelite has been greatly thickened in the lower closure, and the (presumably) calcite marble in front of it displays complicated flow structures. The fold, as well as the marble units below it, can be correlated across the glacier: the fold axis is horizontal, trending NE–SW at variance to the E–W-trend of the "angel" folds.

The semipelite bands below the fold continue with south-easterly dips to the south-west along the cliff-side approximately to the bottom of Qaumarujûp qíngua; one band, shown in Figure 16, may be traced down to sea-level 800 m north-east of the mouth of Agfardlikavsâ; its southerly dip gradually steepens to vertical (strike ca. 80°) near sea-level.

The rocks above ca. 600 m elevation do not contain any markers that can be carried through south-westwards. Dips are variable, but at the level of the middle flank of the "S"-fold the rocks have steep dips to

NW all along the cliff, indicating that the fold structure continues south-west parallel to the cliff. Along the top of the cliff there are several outcrops of folded semipelite, two of which delimit a cliff-parallel hinge zone closing towards SE. It is not possible without information from drillholes to determine if this semipelite can be correlated with that forming the angel, that forming the "S"-fold, or both. If, however, the latter is the case, the Black Angel ore deposit and the sulphide showing at 600 m elevation south-west of the tributary glacier may prove to belong to the same stratigraphic level, probably in the Banded Marble Member (see p. 28).

Structural position of the Black Angel

Apparently the Black Angel and its immediate surroundings are situated in a kind of synform, the "limbs" of which are formed by, to the north, rocks dipping S to SE from the lower half of the formation, and, to the south, the N-dipping thrust which separates the angel area from calcite marble in a high stratigraphic position (Figure 16). The recumbent, tight to isoclinal folds on both sides of the thrust, as well as the folds of the angel itself, may have all formed during one phase of folding in connection with the thrusting.

Small-scale structures

Near the base of the formation where no strong deformation has taken place, impure marbles and clastic rocks are compositionally banded, and there are also massive granular dolomite marbles; generally a more or less distinct foliation is developed parallel to the general bedding. Higher up in the formation several types of small-scale secondary structures occur, which are related to the larger mappable structures.

Cross-cutting foliations

Steeply inclined to vertical cross-cutting foliations are common on the northern flank of the tight fold between the 480 and 746 m lakes, see p. 53. The foliation is particularly well developed in quartz-rich dolomite marble, where the quartz forms closely spaced massive plates about 1 cm thick separated by dolomite (Figure 24). In purer dolomite marble the foliation may be seen as thin layers and veinlets of calcite. Cross-cutting foliations also occur in the Semipelite Member on the Black Angel mountain (see p. 26).

Linear structures: general orientation

Linear structures described in the following, common above the basal part of the formation (measured fold axes, rodding and mineral

Fig. 17. Large S-fold in the Black Angel mountain south-west of the tributary glacier, viewed towards south-west approximately along the fold axis. Black: semipelite; dotted and blank: marble. Not to scale (drawn from a photograph); height of cliff face ca. 700 m.

lineations), have been plotted on the Wulff-net (Plate 4), the whole area being divided up into smaller units separated by faults or geographical distance. Within each unit the plots may diverge up to some 20° from a point maximum; fold axes and lineations generally have similar orientations. The general trend of measured linear structures is ESE–WNW near-horizontal and apparently does not follow the WNW-plunge in the western end of the area of the main syncline. There are only small variations within the whole area, but a change from ESE–WNW to NE–SW-trends occurs between the Black Angel mountain and the small area north-east of the tributary glacier (Plate 4, plots no. 10 and 11). The large scatter in the small subarea no. 6 is due to its structural position wedged in between important thrusts and faults. Further reference to the stereographic plots will be made where appropriate.

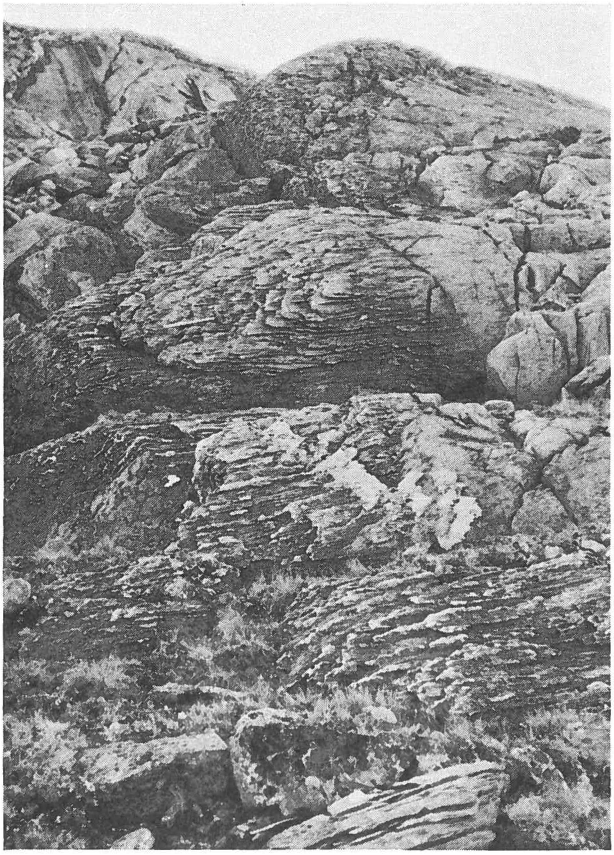
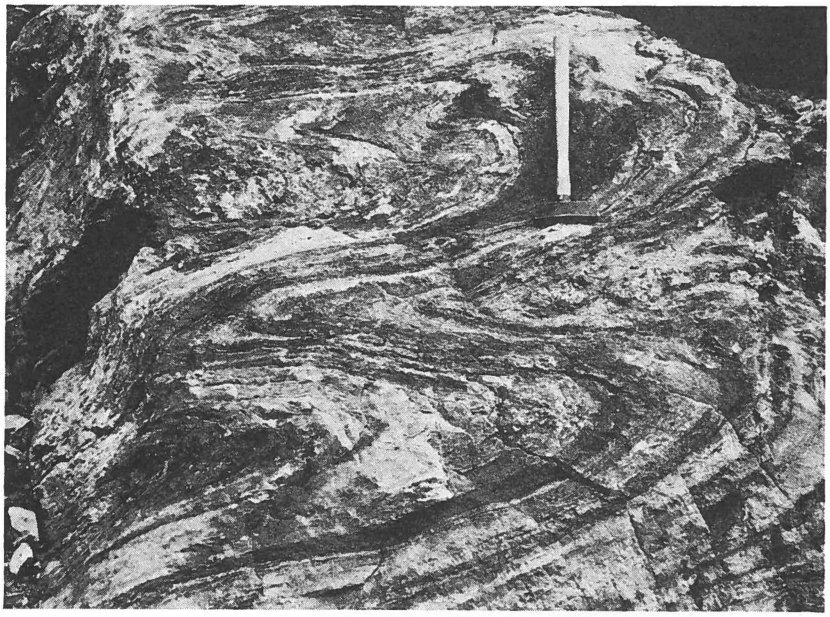


Fig. 18. Quartz rods in dolomite marble; the rodding is almost perpendicular to the steeply inclined quartz-rich bed. Locality 250 m west of the southern tip of the 480 m lake, viewed to the south-west.

Rodding and mineral lineation

Where the hinge zone of the open syncline is exposed between the 480 and 746 m lakes the rocks have a progressively stronger lineation towards its centre: there are both dolomite rods in calcite marble as described on p. 18 and quartz rods in dolomite; in pure dolomite, marbles are entirely composed of indistinct dolomite mineral rods and flags, without consistent planar structures. Also phlogopite mineral lineations are common. Semipelite horizons here are flaggy (though never really schistose) and show fine mica foliations.

Penetrative dolomite and quartz rodding seen as elongate mineral aggregates in impure marble, and also phlogopite lineation, are also found in areas where tight to isoclinal folds on a mappable scale occur, but it is seldom clear if they are related to these, to the open syncline, or were formed independently of both. However, east of the southern end



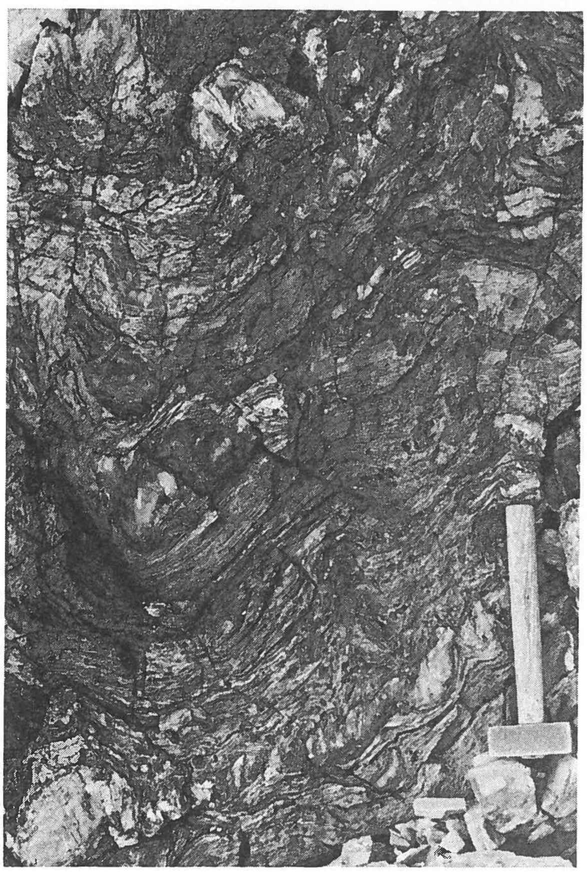


Fig. 19. Examples of minor folds in different lithologies: a) Calcite marble, b) Massive quartz in thinly banded dolomite marble.

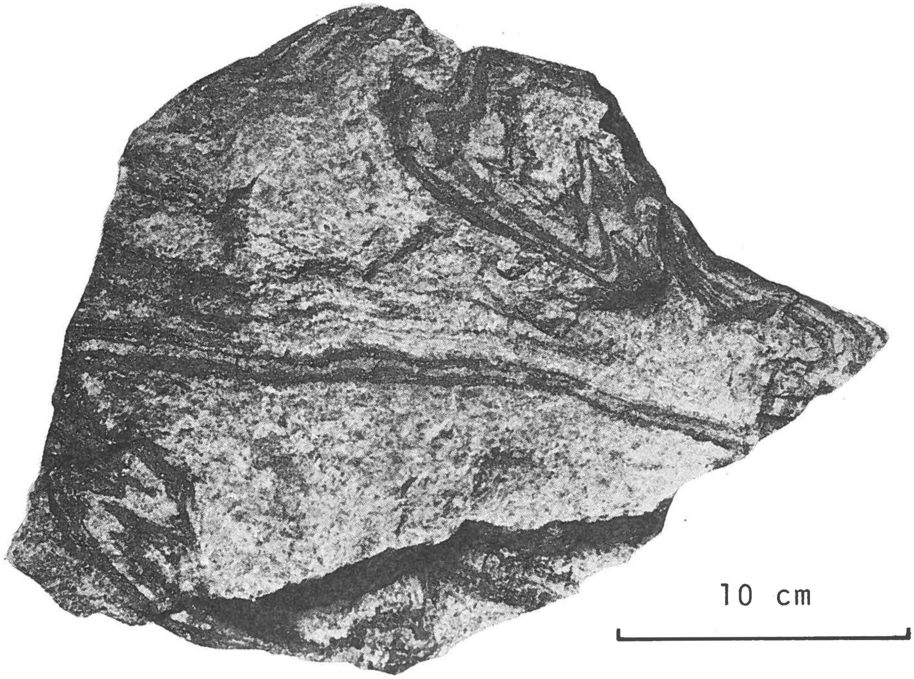
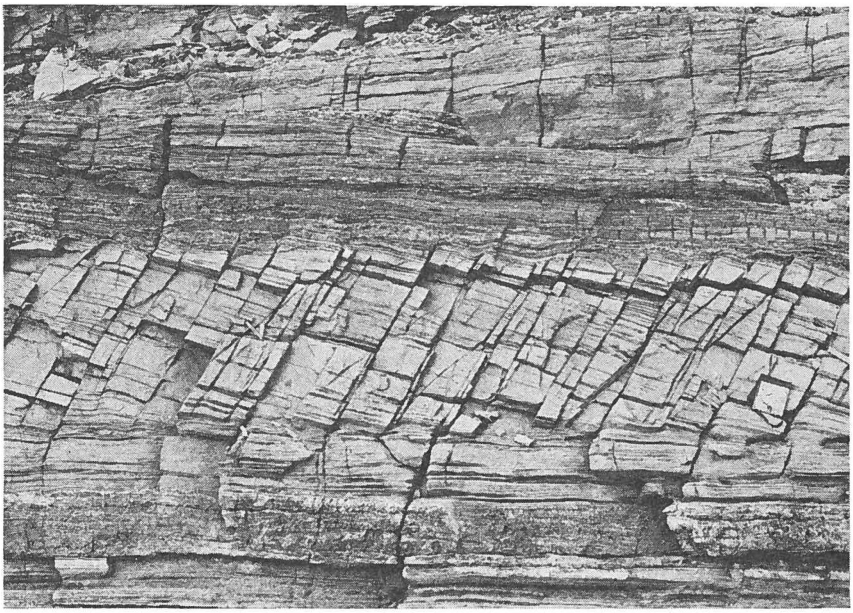


Fig. 20. Example of a minor fold, dark bands of dolomite marble in light calcite marble. GGU 164531, Agfardlikavsâ 2 km south-east of Mârmorilik.

of the 480 m lake quartz rods in dolomite marble (plunge less than 10°, approximately WNW–ESE) form an angle of ca. 90° to the hinge line of a tight, overturned syncline (plunge ca. 15/36) defined by the quartz-rich layers in which the rods occur (see Figure 18 and the stereographic diagram 3a, Plate 4). The rodding coincides with the general linear trend in the area (diagram no. 3) and postdates the tight folding.

Tight to isoclinal folds

Tight to isoclinal folds on a scale of cm to dm are common in the areas where larger folds occur, but are sometimes replaced by penetrative rodding in larger fold closures. The folds are often asymmetric and have varying axial plane orientations (see below), but there are no signs of refolded folds. Examples of minor folds are shown in Figure 19, see also Figure 22 (examples from the tight syncline). Slabs of calcite marble with cm-thick dark dolomite bands (an example shown in Figure 20), sampled at sea level in Agfardlikavsâ 2 km south-east of Mârmorilik, display complicated but homoaxial "wild" fold patterns which conform very well to descriptions of flow-folding and synchronous refolding provided by WYNNE-EDWARDS (1963).



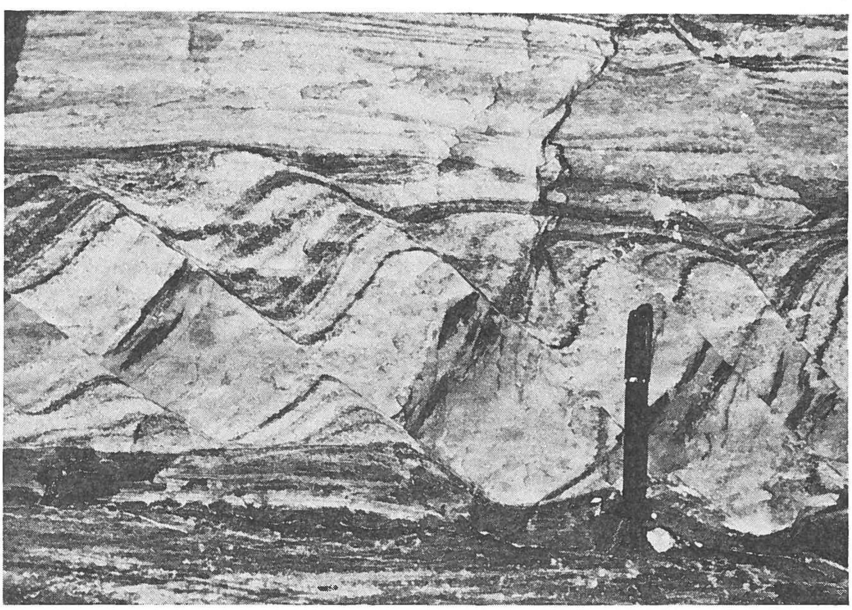


Fig. 21. Jointing and rotation of competent beds of dolomite marble surrounded by mica-bearing dolomite marble, a) near type section 1 ca. 400 m from the base of the formation, b) ca. 300 m north-east of the north-eastern corner of the 480 m lake.

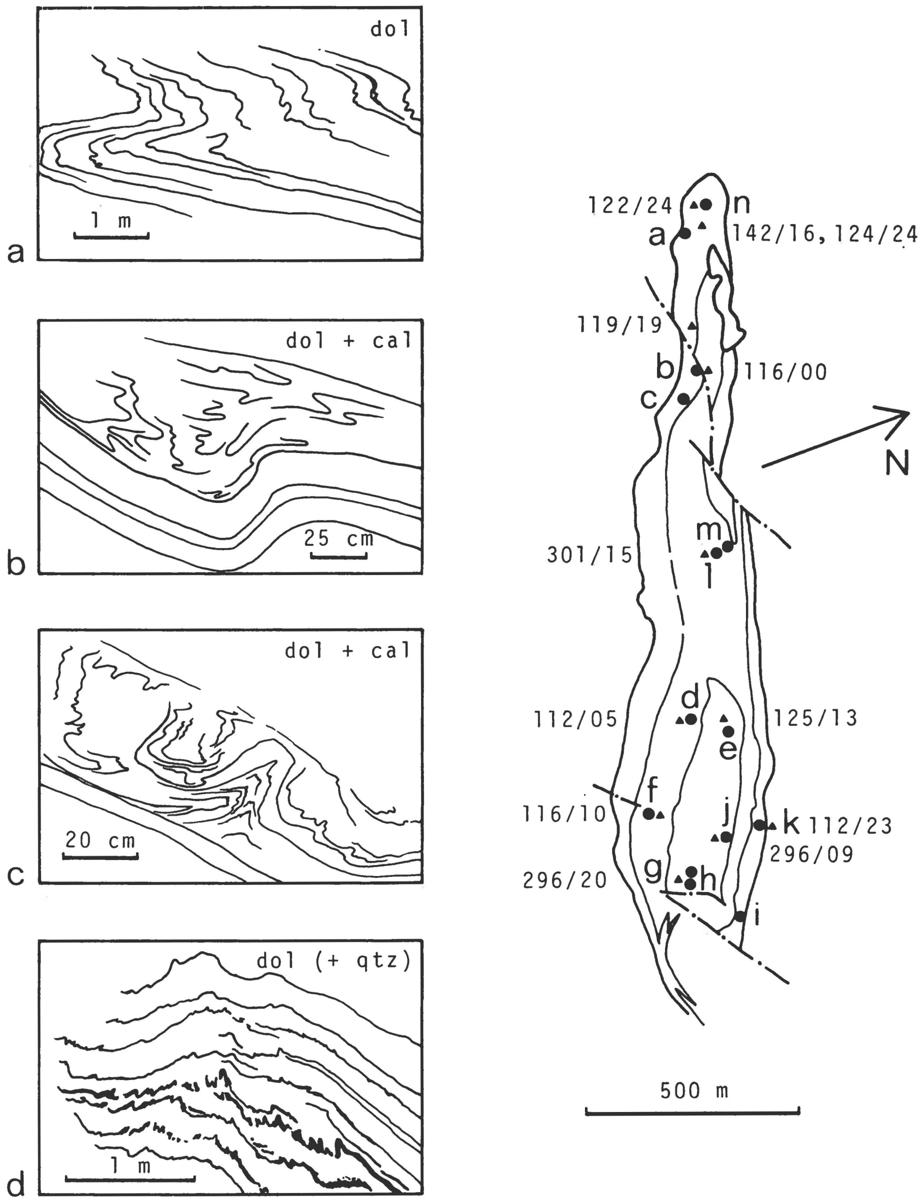
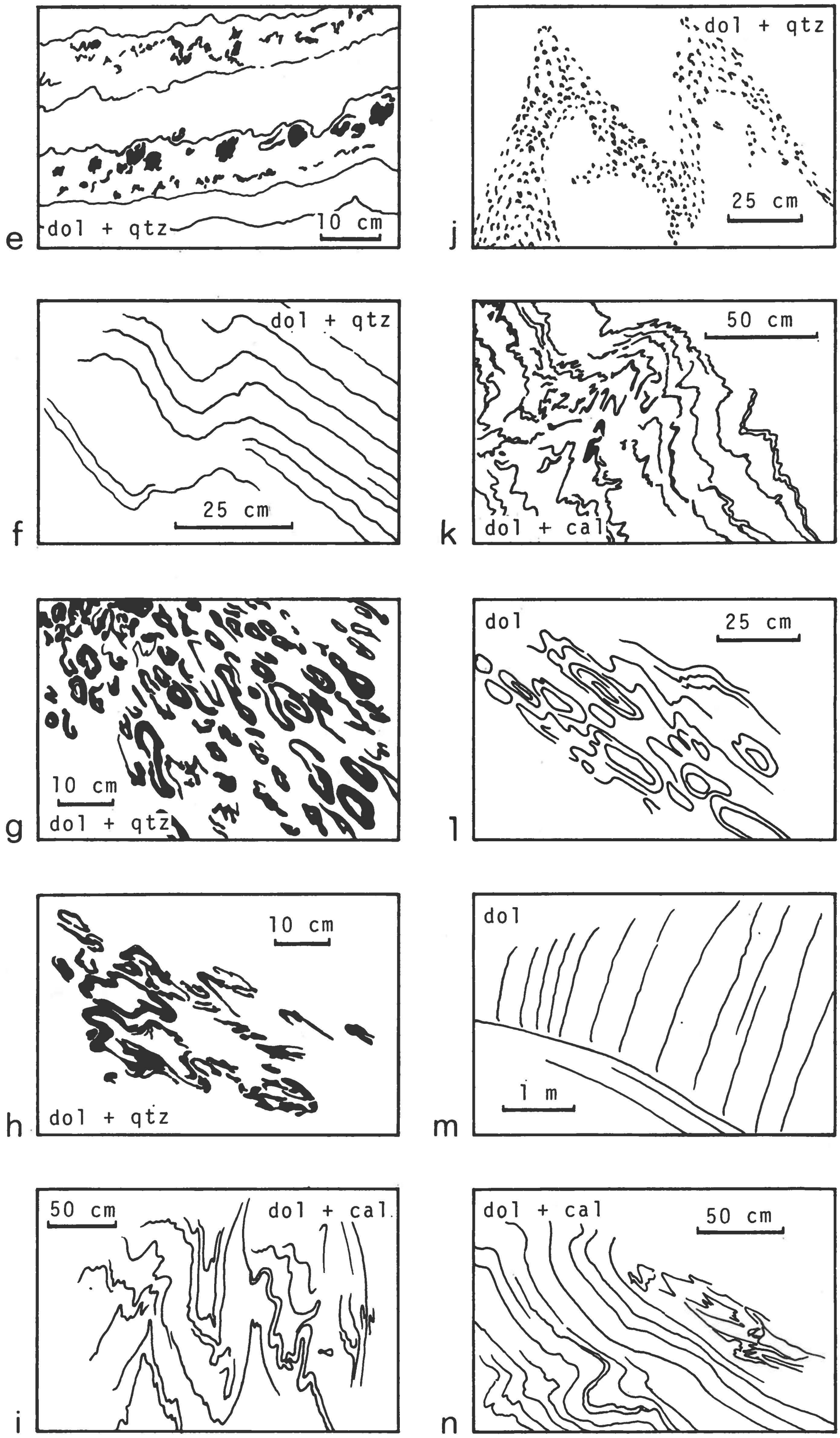


Fig. 22a–n. Minor structures in the tight syncline west of the 746 m lake with locations a–n in the fold (circles). All figures are viewed to the west-north-west parallel to the linear structures. Localities of plunge measurements are marked by triangles. (dol) dolomite marble, (dol+cal) dolomite-calcite marble, (dol+qtz) quartz-bearing dolomite marble.


e
dol + qtz
10 cm
j
dol + qtz
25 cm
f
dol + qtz
25 cm
k
50 cm
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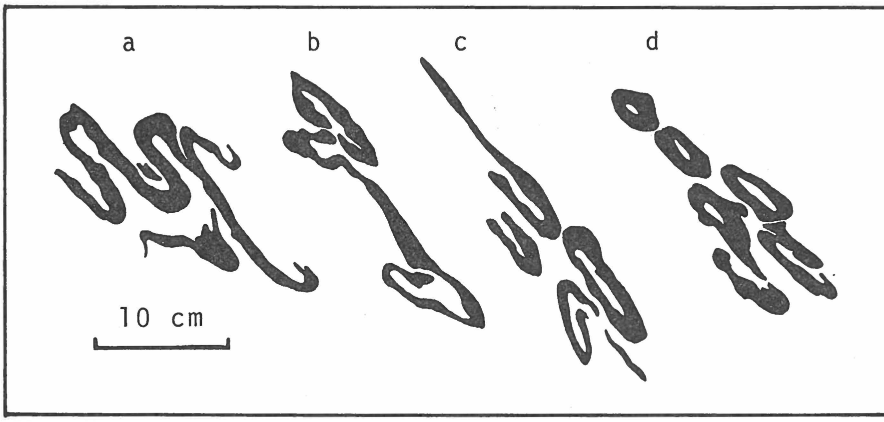

Fig. 23. Stages a–d in the development of quartz pipes from isoclinal folds in dolomite marble. Locality h of Figure 22.

Tectonic breccia

Thrusting has led to the common appearance of broken marble flags and locally to tectonic breccias, for example as described on p. 20 in semipelite-carbonate rocks at the base of a large recumbent fold at the top of the Grey Dolomite Member.

Slip along joints in competent beds

Jointing of competent beds followed by slip and rotation has been observed in several localities in the lower half of the formation (Figure 21). The joint intervals vary from few mm to dm, and the thickness of the beds involved from a few cm to ca. one metre. The structure has been seen in quartz-rich dolomite marble bands (nearly 50 $^0/_0$ quartz), in purer dolomite marble, and in ordinary pure dolomite marble above and below which the marble is rich in mica. The structure is most commonly found south and east of the 480 m lake, where the sense of movement has been determined in a couple of examples: the upper parts of the structures have been displaced eastwards relative to their bases.

Minor structures in the area of the tight syncline

Minor structures are common and well exposed in the area of the tight syncline west of the 746 m lake and were studied in some detail particularly to see if evidence of superimposed folding could be found. Measured linear elements in the western part of the fold follow the orientation of its hinge line (plunge ca. 20° SE); in the eastern part of the fold the linear structures plunge up to 20° W to NW and form an angle of ca. 20° with the hinge line which is here horizontal (Figure 22). On both flanks of the tight syncline there are many minor folds, lineations and axial plane foliations. Some of these are shown in Figure 22 together

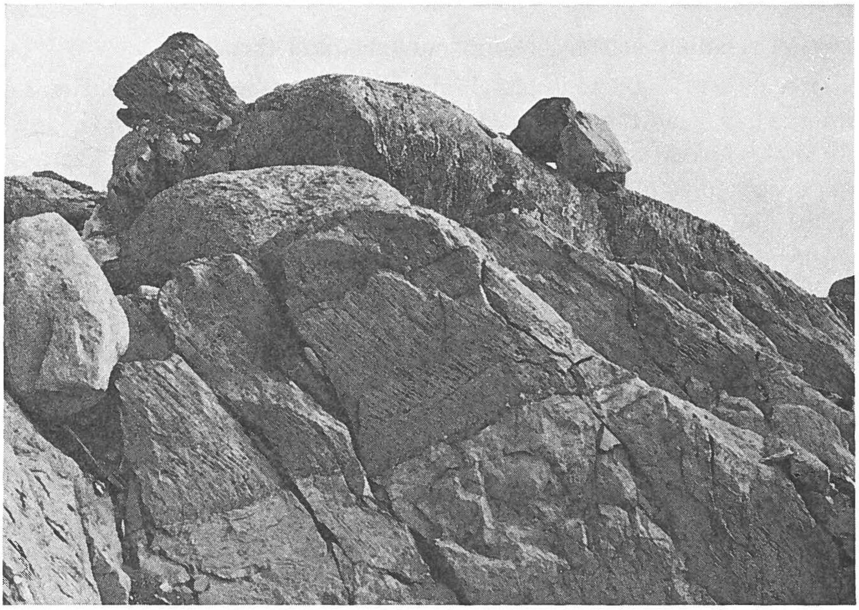

Fig. 24. Steeply inclined foliation in quartz-rich dolomite marble (centre) above dolomite marble (lower right corner) in the tight fold west of the 746 m lake.

with their positions in the fold. The dips of axial surfaces are very variable but on the whole steepest on the northern flank, and the style of folding apparently depends on rock type (chaotic folds with changing axial surface attitudes in banded dolomite-calcite marble, or folds marked by zones of segregated quartz rods in a dolomite matrix); interference patterns due to superimposed folding were however nowhere seen.

A special type of structure, which was found in the hinge zone in two localities in quartz-rich dolomite and almost pure dolomite respectively, is a lineation formed by parallel flat pipes with walls of fine quartz (respectively dolomite) up to ca. 20 cm wide (Figure 22 g–h). In Figure 23 one can see the progressive stages towards the quartz pipes, developed by the fusion of the limbs of tight, rounded folds.

Axial plane foliations (unaccompanied by minor folds) occur north of the thrust boundary of the fold in quartz-rich dolomite marble. They consist of closely spaced, steeply S-dipping quartz plates a couple of cm thick in the dolomite, very similar to the example shown in Figure 24 from inside the fold.

Time relationship between various types of structure

A general idea of the timing of structural events in the Marmorilik Formation east of Mârmorilik may be gathered from local evidence in various parts of the area, which is summarised here.

Common relations between recumbent folds and thrusts

Recumbent, tight to isoclinal folds and thrusts are usually intimately related: they occur together, at restricted stratigraphic levels in the lower half of the formation, and are widespread in its upper parts. There are several examples of recumbent folds with thrusts at their bases, which may be discordant to the structures beneath them. Recumbent folds and thrusts north of the 480 m lake have been refolded by the large open syncline.

Relations between thrusts and the tight syncline

West of the 746 m lake the tight syncline seems to postdate the recumbent folds and thrusts. The prominent thrusts shown on the map in this area are affected by the folding, and the area north-east of them contains penetrative axial plane foliations related to this fold. However, at the same stratigraphic/structural level 2 km further west there occur several thrusts and no upright folds, which rather indicates that at least this thrusting took place during the formation of the fold.

Evidence from linear structures

Measured minor fold axes and lineations east of Mârmorilik cannot be divided into earlier, refolded and later generations, and the rather small variations within the whole area have not been related to other minor structures seen in the field. Nevertheless there is field evidence that at least some linear structures postdate both the recumbent isoclines and the tight syncline just mentioned, forming an angle to fold hinge lines (examples: rodding at the southern end of the 480 m lake, and tubular folds and rodding ca. 500 m west of the 746 m lake). These linear structures are probably contemporaneous with the strong rodding lineation in the hinge zone of the large open syncline, but postdate the open syncline itself (see pp. 46–48).

Faults: relation to other structures

The faults are later than the recumbent folds, and movements along fault surfaces have occurred until very late in the structural and metamorphic history of the formation, as is evidenced by the crushing and growth of talc in the faults. However faulting was already active during later stages of folding. There are also several examples of gradual transitions between thrusting and faulting (e.g. 1.5 km north-west of the bottom of Agfardlikavsâ; 300 m east of the 470 m lake).

The curved trends of the faults east of the 480 m lake may be visualised as resulting from anticlockwise rotations around vertical axes of the easternmost blocks relative to the area west of the 480 m lake, with a cumulative rotation of 25–30° using the base of the Quartzite-Semipelite Member as a datum plane. One might expect that such a rotation was reflected in the orientations of linear elements, but this is not the case; linear structures both south and east of the 480 m lake have similar trends (Plate 4, areas 1 and 5). If rotation has occurred, the greater part must have taken place before the development of the linear structures. Alternatively, the curved shapes of the fault surfaces may have resulted from a combination of transcurrent movements along fault planes and plastic deformation of the individual fault blocks. The joint structures described on p. 52 indicate an eastward movement of the central part of the area relative to its northern and southern margins. In either case some of the fault displacement has occurred before or during the development of the lineation.

Conclusion

The earliest structures seen are recumbent, tight to isoclinal folds accompanied by thrusts, and followed by the tight fold between the 480 and 746 m lakes. The large open syncline is probably later than both. At least part of the rodding and lineation seen formed independently of, and later than, the folds. Faulting was active during, and outlasted, later stages of folding. In general the area is characterised by gradual changes from the development of one type of structure to another. Syntectonic metamorphism is seen in the common quartz and dolomite rodding and mica lineation, but metamorphism outlasted the major structural events (see p. 35).

V. MINERALISATION

Introduction

A description of the Black Angel ore deposit is outside the scope of this account, but the ore deposit is not the only Zn–Pb sulphide mineralisation in the Marmorilik Formation. Some fifty small occurrences of sulphides noted during mapping are marked with red on the map, Plate 7, and more exist. Below a description of the mineralisations and their stratigraphic distribution is given, followed by zinc and lead analyses of ordinary marbles from various stratigraphic levels, and some concluding remarks on the origin of the sulphides.

Descriptions

Low-grade mineralisations

Most of the small sulphide mineralisations in the area are found in dolomite marble as veinlets, a few mm thick, accompanied by secondary, medium-grained calcite and dolomite, sometimes also by quartz, chlorite and talc. Light brown sphalerite and smaller amounts of galena typically are found together (with or without pyrite), but also pyrite-sphalerite and pure sphalerite mineralisations exist. At one locality small amounts of tennantite-tetrahedrite and chalcopyrite were found besides sphalerite.

Showings without pyrite are not easily recognised in the field, as no rust is formed; the weathered sphalerite attains a light red-brown colour, but does not stain the host rock around it. The veinlets are generally conformable with the lithological layering of the marble or form a network of irregular veinlets and patches on a cm-scale; the mineralisations may be followed sporadically along strike for metres or tens of metres, and such showings commonly reappear at several localities at the same stratigraphic level.

Microscopic textures in these typical thin sphalerite-mineralised veins are characterised by equidimensional mm-grained dolomite, calcite and less frequently quartz, with up to few mm large, irregular patches or few cm long continuous bands of sphalerite accompanied by single euhedral, 0.1–0.5 mm large pyrite crystals. Occasionally pyrite forms almost massive, few mm large aggregates separated from the sphalerite. Where galena is present, it is always interstitial and may also be found in dolomite and calcite as tiny veins or trains of inclusions following twin planes and fractures in the carbonate.

The sample GGU 164524, a buff fine-grained dolomite marble at the top of the Lower Dolomite Member (type section 2) contains olive-green sphalerite, tennantite-tetrahedrite and chalcopyrite in mm-thick networks of veins with recrystallised dolomite and traces of calcite and fluorite. Sphalerite and tennantite form irregular intergrowths, or tennantite occurs as anhedral inclusions, size 0.05–0.5 mm, in sphalerite (Figure 25). Chalcopyrite forms veins of its own and, like sphalerite, is also present in minute amounts disseminated in the marble.

Massive mineralisations

Massive sulphide veins, few cm to few dm thick, as well as pyrite lenses a few dm thick, were found in a few localities. One vein, occurring in light grey dolomite marble between the 480 and 746 m lakes (U.T.M. 7886990, 502830), is up to ca. 5 cm thick and may be followed for a few m; it is conformable with the steeply dipping marble, which contains dispersed mineralised veinlets up to a distance of ca. 1 m from both sides of the massive vein. The vein consists of massive sphalerite with small amounts of interstitial galena and a few up to 1 cm large subangular fragments of the host dolomite. In polished sections two exsolved phases, determined as boulangerite ($Pb_5Sb_4S_{11}$) and ullmanite (NiSbS) with the microprobe, were found in and at the borders of 2–3 mm large, irregular patches of galena surrounded by sphalerite. The boulangerite forms rare elongate, anhedral inclusions ca. 0.05 mm long in galena or

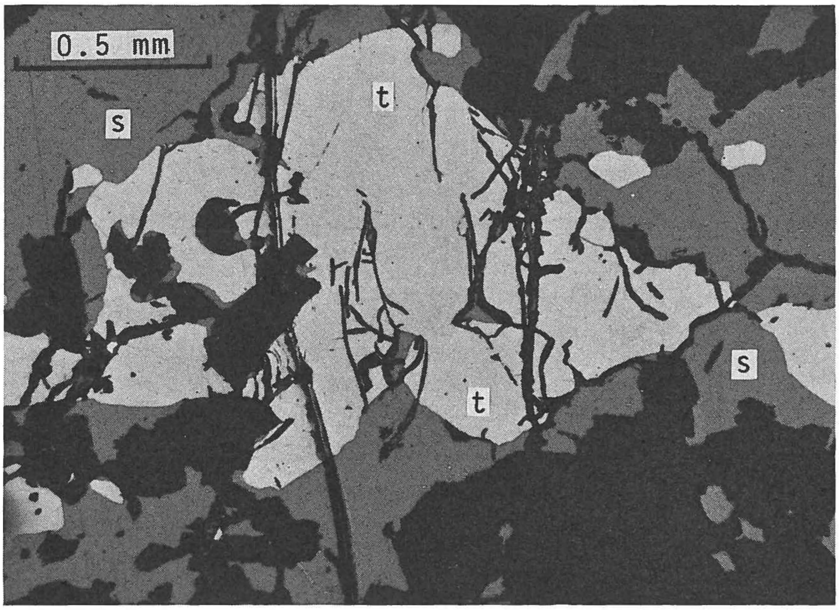

Fig. 25. Tennantite-tetrahedrite (t) in a vein of sphalerite (s); reflected light (GGU 164525).

up to 0.1 mm large aggregates at galena-sphalerite boundaries. A few subhedral equidimensional ullmanite grains ca. 0.03 mm large occur in galena or between galena and sphalerite. Pyrite is rare; it forms sub- to euhedral, up to 0.1 mm large grains and occurs in similar positions as ullmanite.

A second massive sulphide band occurs in the Grey Dolomite Member in the hinge zone of the open syncline ca. 1.5 km north-west of the 746 m lake in an area partly covered by boulders and moraine. The mineralisation is seen as several outcrops on a line following the strike of the marble, which presumably all belong to a continuous, thin layer of Zn–Pb–Fe-sulphides. The mineralisation consists of pyrite and sphalerite with traces of galena; the sulphides are locally accompanied by an up to ca. 50 cm thick footwall border zone of massive, medium-grained calcite.

Textures seen in hand samples vary within few cm from massive pyrite (grain size ca. 1 mm) with interstitial sphalerite to massive, fine- to medium-grained sphalerite with scattered, irregular, up to 1 mm large galena and pyrite grains. Often a weak interbanding of the two types on a cm-scale is present. Black-grey irregular lumps, 1–2 cm large, of fine-grained quartz, galena and pyrite are occasionally seen. Under the microscope the pyrite-rich areas consist of closely spaced pyrite grains (0.5–1 mm large) with very irregular, corroded outlines, generally with rims of sphalerite, but locally with interstitial galena between the pyrite and sphalerite (Plate 3 a–c). No chalcopyrite was found. The pyrite-rich areas grade into massive sphalerite (see Plate 3), sometimes with scattered, anhedral pyrite and/or galena inclusions (size 0.1–0.5 mm), sometimes with galena forming a matrix network for sphalerite on a scale of 1–5 mm. Quartz and calcite form irregularly shaped aggregates up to 1 mm large, which are most common in the pyrite-rich areas.

Stratigraphic control of mineralisations

The sulphide mineralisations mainly occur at distinct stratigraphic levels (with more than a couple of showings), the positions of which are: a) above the second semipelite bed of the Lower Dolomite Member, at and near the boundary between light grey massive dolomite marble and dark grey dolomite (and dolomite-calcite) marble, b) near the top of the Lower Dolomite Member in grey to buff weathering, light grey dolomite marble above quartz-rich dolomite marble, c) above the second semipelite bed of the Grey Dolomite Member (both sphalerite-galena and pure pyrite occurrences). Other mineralisations were found at the base of the Lower Dolomite Member (only massive pyrite), and near the base of the Banded Marble Member (in dolomite). The stratigraphic position of the Black Angel ore deposit is not known with certainty; it is situated in the upper half of the formation, possibly in the Banded Marble Member (see pp. 28 and 44).

Metal contents of ordinary marbles

As shown above the mineralisations are stratigraphically controlled, at least to a certain extent; consequently, the base metal contents of various types of ordinary marble and calc-silicate rocks, particularly at stratigraphic levels where mineralisations are known to occur, are of interest.

Some fifty marble samples without visible traces of mineralisation were analysed for Zn and Pb by atomic absorption spectrometry. The samples were collected at several profiles within the mapped area, but are rearranged in Plate 5 in general stratigraphic order (using the generalised column from Plate 6) together with the positions of the known mineralisations.

The contents of both Zn and Pb are generally low, at or below the average for carbonate rocks quoted as 20 ppm (Zn) and 9 ppm (Pb) by Krauskopf (1967, p. 592). Zn and Pb are positively correlated, Zn being more abundant than Pb, and there is a slight tendency for the enriched samples to occur at stratigraphic levels where mineralisations are known (definite conclusions cannot be drawn about this due to the limited number of analyses). Samples with high graphite contents (in the order of 1 %), GGU 164408, -424, -440, -442, -448, -449, -453, -454, -462, -468, -477, -523, are sometimes (but not always) enriched, particularly in Zn. Calcite marbles only rarely have high Zn and Pb contents. A marble breccia (GGU 164420) and a talc schist (GGU 164444) from faults are both very low in Zn and Pb.

Conclusions

The following facts are characteristic for Zn–Pb sulphide mineralisations in the Marmorilik Formation: a) The mineralisations are stratigraphically controlled, in marble; b) there are several mineralised horizons, occurring in marbles with slight indications of general Zn- and Pb-enrichment; c) sphalerite and galena are generally found together, with or without pyrite; (d) the mineralisations mainly occur in dolomite marble (often graphite-bearing); e) evidence exists of some lateral mobilisation and concentration near hinge zones of folds (both in early, isoclinal folds and the large open syncline); f) the mineralisations are not associated with late faults. It is not known to the author whether the host rock of the Black Angel ore deposit is predominantly dolomite or calcite marble, but otherwise the ore deposit does not seem to differ from other mineralisations except in size.

The above points indicate, or are compatible with, a syn- or epigenetic origin of the base metals; a secondary hydrothermal origin is ruled out simply because no suitable magmatic source exists. This does not necessarily imply, however, that the mineralisations were originally deposited in their present form — on the contrary the massive occurrences were almost centainly mobilised into their present, structurally controlled positions from strata with sufficiently high lead-zinc contents. It is difficult to propose a definite mechanism of deposition for the metals because no primary structures have survived in their host rocks. Most likely they are chemical precipitates, precipitation being the most important "trapping mechanism" in sediments for both zinc and lead (Förstner & Müller, 1974). If the metals were supplied in dissolved form from nearly neutral, weakly oxidizing waters, they may have first precipitated either as sulphides by a decrease in Eh, or as carbonates by a rise in pH (Förstner & Müller, 1974, p. 150). It is possible that sulphate-reducing bacteria have been active in the iron, zinc and lead sulphide formation and supplied the necessary reduced sulphur. The possibility also exists that the rather widespread graphite represents remains of organisms, see p. 62 (?nutrients for the bacteria). However, as mentioned there is no clear-cut correlation between graphite and base metal contents.

The base metal precipitation may have taken place either during the primary carbonate deposition or together with a subsequent dolomitisation. The problem of the origin of the dolomite in the Marmorilik Formation is discussed on pp. 65–66, where it is concluded that diagenetic dolomitisation, possibly by seepage refluction, is the most probable explanation.

Analytical procedure

Zn and Pb analyses were carried out with a Perkin-Elmer 300 atomic absorption spectrophotometer, and the metal contents were corrected for influence by calcium. Repeated analyses gave relative differences in the order of 5–10 ‰. Cu, Ni, Mn and Fe were analysed by emission spectrography using the lines at 3247, 3414, 4030 and 3021 A respectively (analytical details as in GARDE, 1979).

VI. ORIGIN OF THE MARMORILIK FORMATION

Regional aspects

Once established that the Marmorilik Formation is not an integral part of the Umanak gneiss, it became clear that it most likely is related to the Karrat Group to the north (Figure 1), which has been described by HENDERSON & PULVERTAFT (1967), and its most probable correlative is the Qeqertarssuaq Formation (GARDE & PULVERTAFT, 1976). The Marmorilik Formation however is much less diverse than the Qeqertarssuaq Formation, and contains less clastic material and no amphibolites. Moreover the Qeqertarssuaq Formation is very thin in the areas where it is nearest to the Marmorilik Formation. Clearly the Marmorilik Formation must have been separated from the Qeqertarssuaq Formation by an effective barrier during most of its deposition, and presumably was laid down in a shelf basin with little clastic input.

Some characteristics of the Marmorilik Formation relevant to its origin

Well-preserved Phanerozoic sedimentary carbonate rocks are classified and interpreted according to primary sedimentary structures and microscopic textures, as well as fossil content (FOLK, 1959; DUNHAM, 1962), an approach which for obvious reasons is not applicable here. A uniformitarian comparison is hampered by the fact that the formation of modern carbonates is governed by a multitude of organisms, whereas the role of Precambrian organisms on carbonate formation is quite uncertain.

There are also difficulties involved in comparing the Marmorilik Formation with the best known carbonate formations of similar age on account of the poor state of preservation of primary features in the Marmorilik Formation due to deformation and metamorphism. However, there are some general characteristics of the formation that are considered relevant to a discussion of its origin; these are recapitulated below.

Distribution of calcite and dolomite marble

During the detailed mapping it became clear that the distribution of calcite and dolomite marble follows the clastic markers as noted on p. 9 (see Plate 7). For instance, the Thin Calcite Marble Member may be followed along strike through the mapped area for more than 7 km through various fault blocks and has been folded and thrusted together with the enveloping dolomite marbles. Also the boundary between the Banded Marble Member and the Massive Calcite Marble Member is sharp and predeformational as may be seen for example in the recumbent fold north-west of the 480 m lake. Only in the upper part of the north face of the Black Angel mountain is the distribution of calcite and dolomite marble in some places unmappable due to complicated flow structures and unaccessibility (Figure 17).

For this reason the general stratigraphy and the occurrence of the various types of marble as layers of large lateral extent conformable with the clastic markers seem to have been established before deformation and metamorphism.

Massive, weakly banded carbonates with graphite and/or pyrite

Very large parts of the Marmorilik Formation are calcite and dolomite marbles that are massive to weakly banded, contain thin silicate-rich horizons (which may have originated by stylolite growth), are almost invariably pyrite-bearing, and often contain graphite in amounts up to around 1 $^{0}/_{0}$. Boundaries between graphite-rich and -poor carbonates may be sharp or transitional without other noticeable changes. In calcite marbles lateral changes in graphite content frequently occur. These rocks are all comparable to the larger part of the ca. 2100 m.y. old Dolomite Series in the Transvaal "System" of the Northern Cape Province, South Africa (Toens, 1966, pp. 7–9). According to Toens, there is no reason to assume that the uniform, massive to weakly banded character of the larger part of the Dolomite Series is of secondary origin (unlike the coarse-grained variety described by Toens, op. cit. pp. 9, 14–15). Toens (1966) argues that the horizontal laminations of carbonaceous matter in the fine-grained Transvaal dolomite and calcite rocks are of algal origin and developed in situ in the photic zone, covered by relatively shallow water. However, weakly laminated, fine-grained carbonate rocks with fragments of organic matter may also be deposited under deeper water (WILSON, 1969).

It has not been established that the graphite in the Marmorilik Formation is of biogenic origin, but the carbon isotope data is consistent with such an origin (GARDE, in press).

Absence of stromatolites

Stromatolites are commonly found in Precambrian sedimentary carbonate rocks. They are particularly abundant in the basal and uppermost parts of the Dolomite Series of the Transvaal "System" where they are associated with algal filaments (TOENS, 1966), and in the Coronation geosyncline where they occur in several hundred metres thick platform dolomites interbanded with dark shaly dolomite (HOFFMAN, 1973). The stromatolites may be composed of alternating calcite and dolomite (TOENS, 1966, p. 37) or of dolomite and quartz or chert. Precambrian stromatolites are believed to indicate shallow water or intertidal deposition by analogy with Recent stromatolites.

Although stromatolites have not been recognised in the Marmorilik Formation it cannot be precluded that they have been present. Banded dolomite-quartz rocks might be produced by deformation of stromatolite structures such as those shown by HOFFMAN (1973, fig. 7a), and the dark banded dolomite-calcite marbles such as are seen in the upper part of the Lower Dolomite Member of the Marmorilik Formation could also be remnants of stromatolites.

Distribution and possible significance of scapolite

Prismatic, cm-sized crystals of scapolite, and pseudomorphs after scapolite (see p. 29), are common in the dolomite marble, and were found in a few localities in calcite marble. The scapolite is not restricted to certain stratigraphic levels, but is particularly common in the dark grey marbles above the second semipelite horizon in the Lower Dolomite Member, and near the base of the Grey Dolomite Member. The fresh scapolites have moderate birefringences around 0.015, corresponding to compositions around Me_{35} (TRÖGER, 1971), and sometimes show weak zoning. An analysed crystal from the Massive Calcite Marble Member (see p. 32) is a chlorine-rich variety with the composition Me_{27} (centre) to Me_{38} (rim).

SERDYUCHENKO (1975) for one has pointed out that scapolite in metamorphosed carbonate rocks may represent premetamorphic evaporitic minerals, and later KWAK (1977) has investigated the change in the chemical compositions of scapolites from non-evaporitic rocks along metamorphic gradients from upper greenschist facies (Me_{40}–Me_{50}) into amphibolite facies (up to Me_{75}); he suggests that scapolites richer in K, Na and Cl than would be expected from this trend are indicative of original evaporitic conditions. Unfortunately the data in KWAK (op. cit.) are rather limited and do not cover the full range of the greenschist facies, and with scapolite analyses from only one sample in the Marmorilik Formation nothing definite can be said from scapolite alone. However, during recent investigations in the Black Angel mine, an up to 60 m thick unit of marble with calcium sulphate minerals was found (F. D. PEDERSEN, pers. comm.). This marble unit has not been found on the cliff-faces outside the mine, and has not been seen by the present writer.

Semipelite-banded carbonate rocks, semipelite and related rocks

Several thin, persistent, finely laminated semipelite beds are present in the Marmorilik Formation, and in the upper part of the formation thicker banded semipelite-carbonate sequences occur. When these rocks were laid down the area of deposition must have been completely covered by water. The thin pale cherty bands described on p. 18 are considered to be clastic rocks because they occur as regular beds with constant thicknesses and because there are examples with compositions intermediate between semipelite and almost pure quartzite. Also their grain sizes are similar to the finer-grained varieties of semipelite.

Quartz in the Marmorilik Formation

Quartz is commonly present in impure dolomite marbles in the formation, particularly in the following situations: a) Near the base of the formation there is a gradual transition from clastic rocks to dolomite marble with quartz layers a few cm thick that are recrystallised into granular aggregates with grain sizes of 0.2–1 mm. Some quartz was consumed by tremolite-forming reactions. Associated with the quartz are albite and phlogopite; potassium feldspar is rare compared to albite, but this is almost certainly due to metamorphic reactions. There is no reason to believe that the silicate material in these impure marbles was not delivered by clastic sedimentation, possibly assisted by stromatolite growth. b) Banded dolomite marbles with quartz contents in the order of 20 $^0/_0$, but little phlogopite, are also met higher up in the formation and may be traced laterally throughout the area. c) Thin cherty bands with compositions near to pure SiO_2; these have been dealt with in the previous section. d) Many metres thick units of quartz-rich dolomite marble are met in the Massive Calcite Marble Member (see pp. 22 and 24); these do not resemble those under a) and b). Under the microscope two types of quartz are seen: 1) fine-grained quartz in the dolomite, occurring as small patches and streaks associated with albite and phlogopite and believed to be clastic, and 2) massive, medium-grained quartz which clearly has been mobilised (Figure 5) and which may represent diagenetic replacement bodies.

Origin of the carbonates in the Marmorilik Formation

From the preceding sections it is evident that only a few definite conclusions can be drawn about the origin of the carbonates in the Marmorilik Formation; the main aim of the discussion to follow is to show that there is no reason to propose that processes of carbonate formation other than those which are known or likely to be taking place today were operative in the Marmorilik Formation.

Primary calcium carbonate

The present distribution of calcite and dolomite marble suggests that the two types of marble existed as layers conformable with the clastic markers before deformation and metamorphism (p. 61). It has also been shown from a study of the distribution of strontium in the marbles (GARDE, in press) that the calcite marble was not formed by metasomatic dedolomitisation of a dolomite precursor, but originated as a calcium carbonate limestone; the dolomite, on the contrary, may well have formed by diagenetic dolomitisation of a calcium carbonate precursor (see also below). Therefore it may be assumed that much or all of the carbonate in the Marmorilik Formation was deposited as calcium carbonate limestone.

Conditions of deposition of the carbonates

a) The role of organisms

Calcium carbonate may be precipitated chemically from supersaturated solutions when the pH has risen due to extraction of CO_2, a process which is taking place today in lacustrine environments around photosynthesizing plants, or when travertine is formed. In modern oceans, however, precipitation of $CaCO_3$ is performed by carbonate-secreting organisms. Biogenic dolomite sensu strictu is only known from the teeth of sea urchins, but many organisms secrete calcite with several percent $MgCO_3$ in solid solution, and algal limestone with as much as 24 $^0/_0$ $MgCO_3$ is known. Shell-secreting organisms are unknown from the Lower Proterozoic, but it may well be that the carbonate of the Marmorilik Formation was precipitated as a result of the extraction of CO_2 by plants capable of photosynthesis, most likely blue-green algae, regardless of whether the organisms were living on a sediment surface or were planktonic. Alternatively, or in addition, carbonate may have been secreted in the tissue of bottom-dwelling or planktonic algae; a large variety of marine algae can produce minute aragonite needles which are morphologically indistinguishable from inorganic precipitates (LOWENSTAM & EPSTEIN, 1957).

b) Water depth

The question of water depth is difficult to solve, but in relation to possible modes of dolomite formation it is important to consider whether the deposition of the Marmorilik Formation took place in a shallow water-intertidal environment or under a more permanent cover of water. Unfortunately not even this question can be answered with certainty.

Positive evidence for shallow water deposition (conglomerates, cross-bedding and wave-ripple marked surfaces) is only found within a few metres from the base of the formation. As already mentioned, the presence of stromatolites has not been proved in the Marmorilik Formation, but the banded dolomite-calcite rocks and some dolomite-quartz rocks could nevertheless be shallow water or intertidal deposits.

The general character of the massive or weakly banded carbonates, both dolomite and calcite marble, which make up the largest part of the formation, is however just as consistent with an origin as fine-grained carbonate muds formed at some depth below a permanent water cover as with an origin at shallow depths. The widespread pyrite and graphite in the Marmorilik Formation is evidence that much of the sedimentation took place under reducing conditions, which however does not necessarily imply great water depths; water circulation and the oxygen content of the atmosphere at the time of deposition are critical and unknown factors, so no safe conclusions can be drawn from this point. The deposition of the thin semipelite beds as well as the Semipelite Member must have taken place under a permanent cover of water.

c) Dolomitisation

The heading of this subsection implies that the formation of dolomite in the Marmorilik Formation took place by replacement of original calcium carbonate (see p. 64). Primary dolomite precipitation apparently does not take place in the sea today. If it took place in Precambrian times, the magnesium to calcium ratio and salinity of Precambrian sea water must locally have been considerably higher than today, according to what can be inferred from experiments and Recent natural environments where dolomite is formed (see below). The salinity and the relative proportions of magnesium and calcium in sea water during the Precambrian and their implications for the deposition of various carbonate species have been discussed by numerous authors. The present writer holds the view that if the formation of dolomite in the Marmorilik Formation can be explained by a process similar to any of those thought to be operating today, there is no need to make the speculative assumptions necessary for a direct precipitation model (see Holland (1972) for a discussion about this point).

The fact that dolomite rocks are now found in units representing a wide variety of depositional facies has led ZENGER (1972) to conclude that diagenetic dolomitisation must have taken place in many dolomite rocks. The only well-established Recent, naturally occurring process of dolomite formation is that occurring in the upper metre or so of supratidal coastal sabkhas, for example around the Persian Gulf (ILLING et al., 1965). The dolomite is formed by replacement of aragonite, and apparently the most important conditions for the replacement are the salinity and Mg/Ca ratio in the surroundings where dolomite is formed; in sabkha environments evaporation and gypsum precipitation raise these to values several times higher than in normal Recent sea water.

LIEBERMANN (1967), in a frequently cited series of experiments, was able to precipitate dolomite by a two-stage process under conditions which seem to be fulfilled with regard to salinity ,Mg/Ca ratio and diurnal temperature changes in the uppermost few cm of the sabkha (BUTLER, 1969). However, during LIEBERMANN's experiments the temperatures were generally some 10° lower than near the surface in a sabkha.

Dolomitisation by seepage refluction, a hypothesis put forward by ADAMS & RHODES (1960), has not so far been proved to take place in nature. A suggestive environment was described by DEFFEYES et al. (1965), but the postulated refluxed brines were not met in drill-holes (LUCIA, 1968). Nevertheless the seepage reflux hypothesis has become very popular.

Either, or both, of the two processes of dolomitisation mentioned may have been active in the Marmorilik Formation. Both processes require arid, evaporitic conditions; the presence of scapolite and the recent discovery of evaporite minerals in the Black Angel mine take on an added significance in this context. Several other arguments could be presented about various processes of primary and secondary formation of dolomite, but the present state of preservation of the marbles does not lend itself to any definite conclusion. The present writer is of the opinion that early diagenetic dolomitisation (?by hypersaline sea water refluction) is the most likely alternative of those discussed; at least there is no need to make speculative assumptions about primary dolomite precipitation.

The Marmorilik Formation in the context of Precambrian carbonate formations

There is no doubt that both Archaean and Lower Proterozoic sedimentary carbonate rocks exist in all the Precambrian shields of the world, but only in few cases is their depositional age known with reasonable certainty. Precambrian carbonates are generally believed to consist mainly or wholly of dolomite. Judging from notes and brief descriptions of a number of occurrences this seems generally to be true, but unfortunately one cannot always be sure about the relative amounts of calcite and dolomite in a given formation from loosely used terms like "dolomitic marble", "dolomitic limestone", or simply "marble".

Carbonate formations of Archaean or probable Archaean age from South-West Greenland, the Canadian shield, the Siberian platform, Southern Africa and the West Australian Shield are thin, maximum a couple of hundred metres thick, and generally consist of dolomite (Allaart, 1976; Armstrong, 1960; Nalivkin, 1973; Brown et al., 1968; Truswell, 1970; The Geological Survey of Western Australia, 1975), but occurrences of almost pure calcite also exist, notably in the more than 2700 m.y. old Bulawayan Huntsman limestone (Bond et al., 1973) in Southern Africa.

The first really large carbonate formations, with thicknesses measured in hundreds of metres or even in kilometres, were deposited during the Lower Proterozoic. There are both platform and geosynclinal occurrences, the former often associated with banded iron formation. Some examples of presumed or definite Lower Proterozoic age are the Dolomite Series, Transvaal "System", which in the Northern Cape Province contains a more than 100 m thick pure calcite limestone unit near its top (Toens, 1966), the dolomites from the Coronation geosyncline, the Huronian Espanola Formation, Canada (Young, 1973), the Fedorovskian Suite in the Aldan massif and the carbonates of the South Baikal region, U.S.S.R. (Nalivkin, 1973, pp. 200–203), the carbonates of the Gangpur Series, Orissa, India (Rao et al., 1964) and the Duck Creek Dolomite, Wyloo Group, Western Australia (Trendall, 1975, p. 136). Abundant stromatolites are typical particularly for the carbonates of the U.S.S.R. (referred to as "calcareous algae"), but also homogeneous, weakly bedded, unfossiliferous, pale or dark grey carbonates are common.

The Marmorilik Formation ranges clearly among these early large carbonate formations. Several others have similar or larger lateral extents, but only one, the Dolomite Series, Transvaal "System" is known by the writer to be considerably thicker than the Marmorilik Formation, with a maximum thickness between 3 and 4 kilometers. The general massive to weakly banded character of the Marmorilik Formation carbonates is comparable to the non-stromatolitic types of well-preserved Precambrian carbonates; more unusual are its relatively high proportion of almost pure calcite rocks, and the lead-zinc deposits; lead and zinc ores are common in younger carbonate rocks, but rather scarse in the Proterozoic (Sangster, 1976, p. 448). The Marmorilik Formation appears to be a platform deposit, resting on an eroded surface of granodiorite and gneiss; in many respects it is comparable to the Dolomite Series, Transvaal "System".

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PLATES

Plate 1

Oblique aerial photograph of part of the Marmorilik Formation viewed to the north-east. In the left centre the Black Angel mountain. Scale in the centre of the picture ca. 1:40 000. Reproduced by permission of the Geodetic Institute, Copenhagen (A.730/77). Photograph 514 M–NØ 5461. COPYRIGHT.

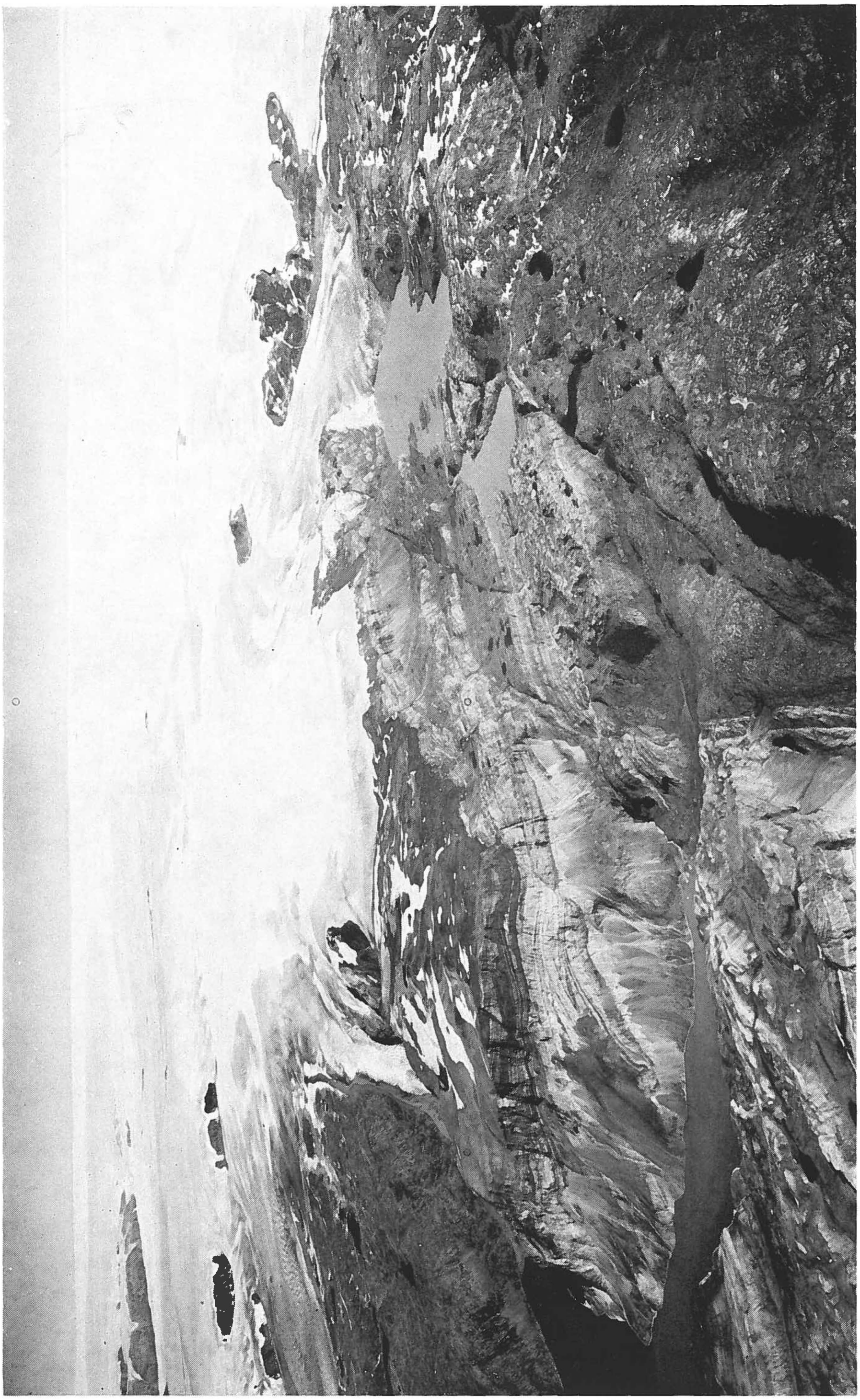

Plate 2a

The basal sequence of the Marmorilik Formation, type section 1, viewed towards the west: to the left the basal unconformity and the Quartzite-Semipelite Member (dark) followed by impure dolomite marble units (centre) and a thin semipelite bed (right). The snow patches delimit a transcurrent fault. In the right-hand background massive calcite marble capped by semipelite and ice (see Plate 2, fig. 2b).

Plate 2b

The upper half of the Marmorilik Formation viewed towards the north-west across the 480 m lake. Most of the cliff-face is composed of calcite marble (light) and semipelite-banded calcite marble (darker shades) belonging to the Massive Calcite Marble Member. The marbles are capped by dark semipelite (the Semipelite Member) and Inland Ice. The cliff-face is 600–700 m high.

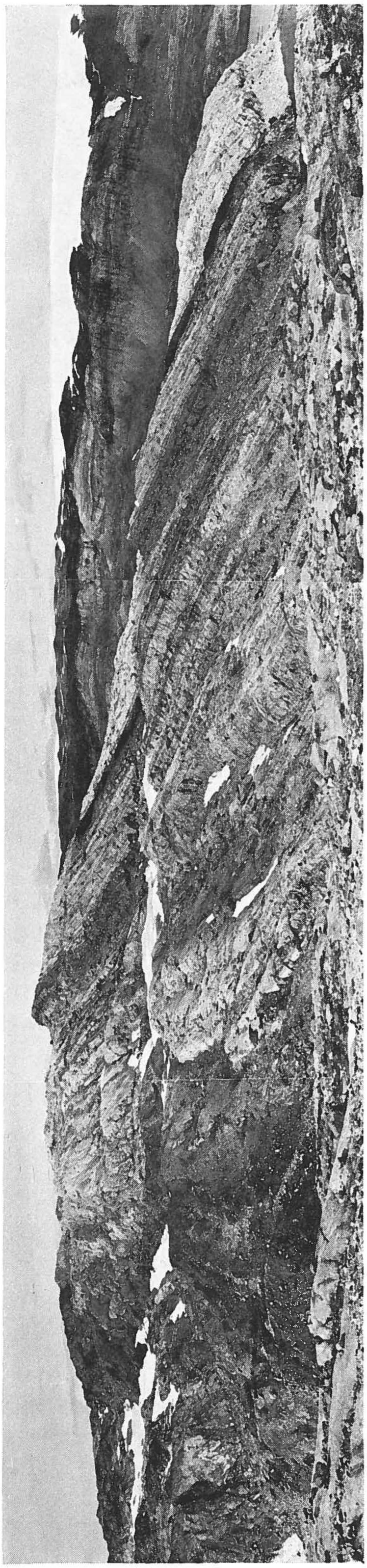

Fig. 2a

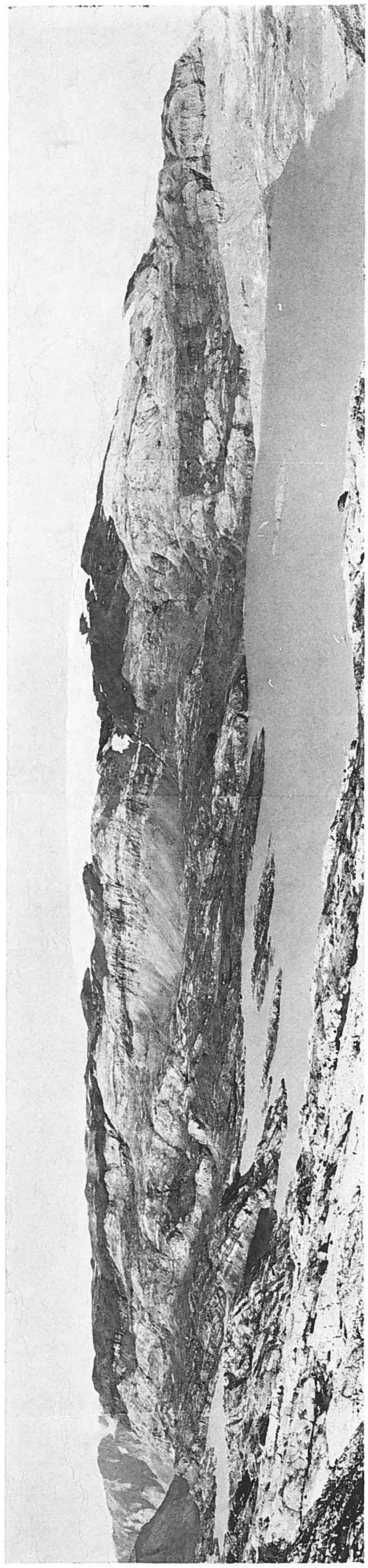

Fig. 2b

Plate 3

Massive sulphide mineralisation, three stages from granular pyrite with interstitial sphalerite and galena (top) to replacement of pyrite by sphalerite (bottom). (p) pyrite, (s) sphalerite, (g) galena; reflected light (GGU 164505).

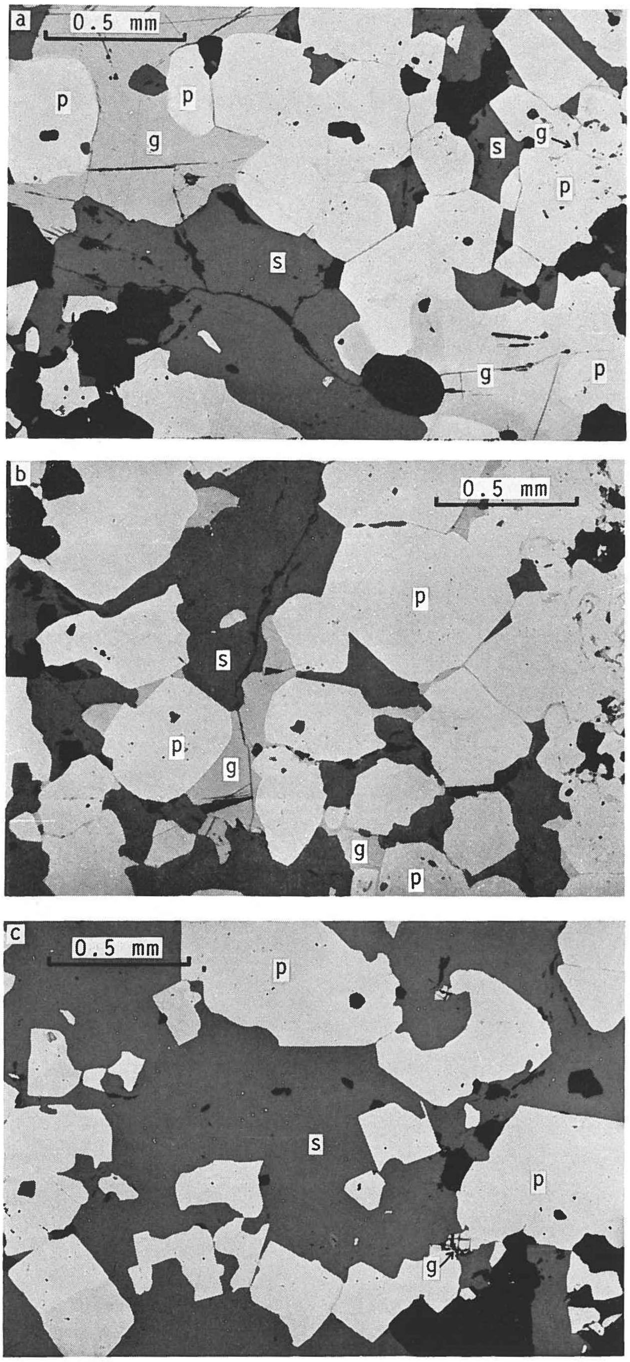
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Plate 4

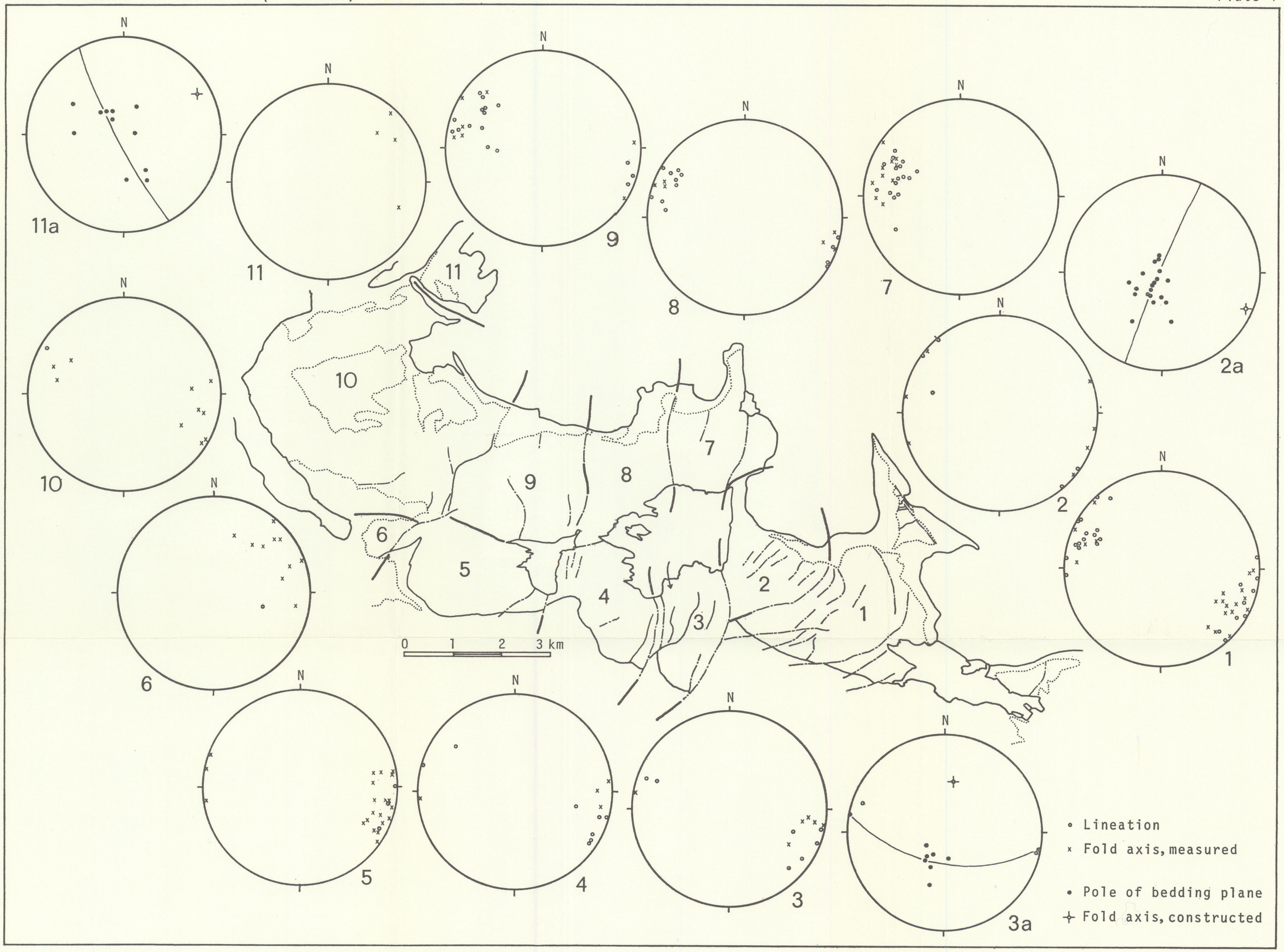
Measured linear structures in subareas 1–11 east of Mârmorilik, plotted on a Wulff-net. The additional diagrams no. 2a, 3a and 11a show poles of bedding planes and constructed fold axes. Note in diagram no. 3a the opposing directions between measured lineations and the constructed axis of a small fold.

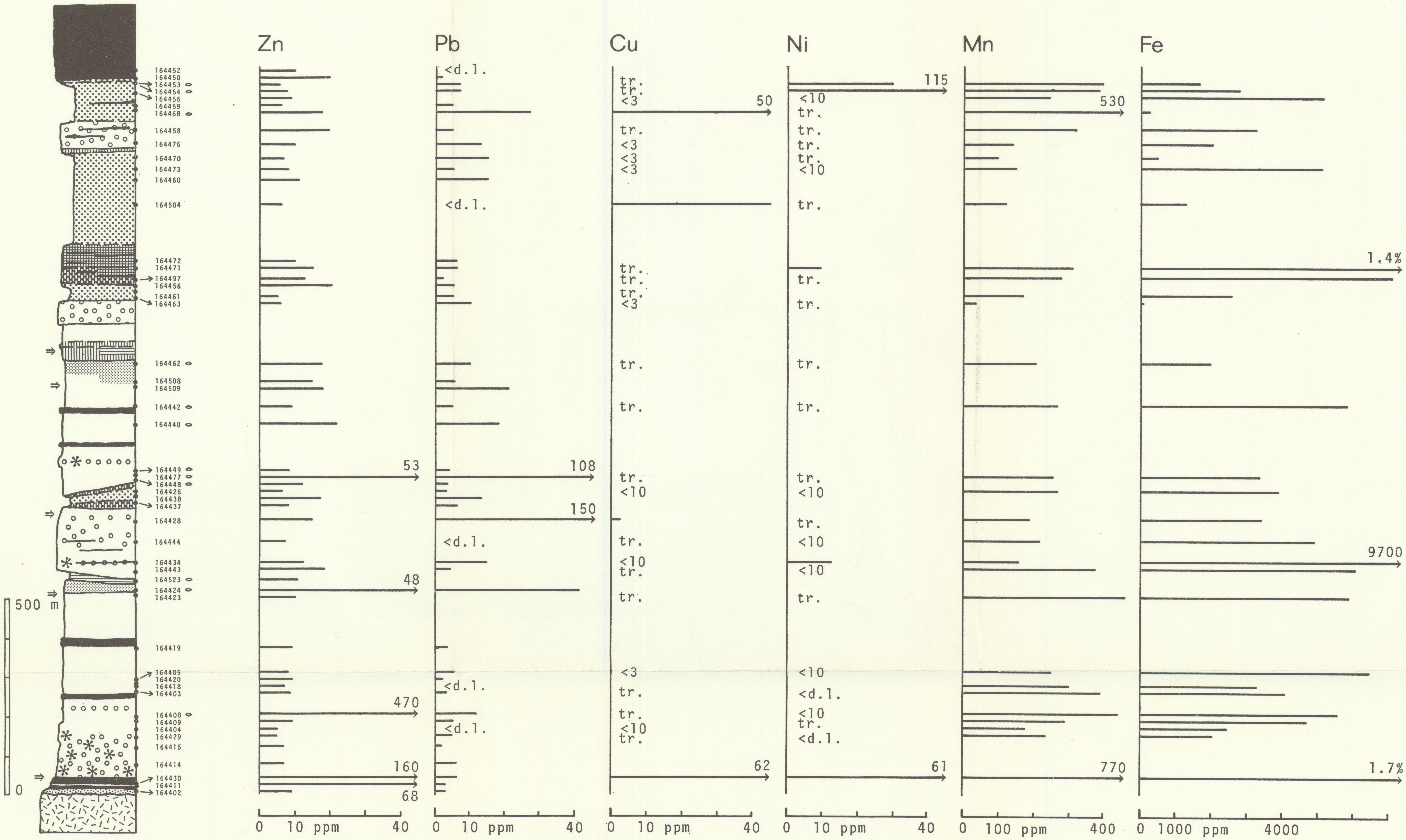
Plate 5

Generalised stratigraphic column of the Marmorilik Formation (from Plate 6) with mineralised horizons (arrows, left) and Zn, Pb, Cu, Ni, Mn, and Fe contents of ordinary marbles and calc-silicate rocks (right). See Plate 6 for a legend of the stratigraphic column; note the variable scales for metal contents. Zn and Pb were analysed by atomic absorption spectrometry, the other elements by emission spectrography.

Plate 6

General stratigraphy and correlation of the Marmorilik Formation east of Mârmorilik. For easy comparison of stratigraphy the relative positions of the cross-sections reflect their general sequence from east to west, but do not follow strict rules. The lateral distances between the stratigraphic columns are corrected for fault movements and are approximately true along strike.


N
11a
11
9
8
7
2a
10
2
6
1
5
4
3
3a
10
11
9
8
7
6
5
4
3
2
1
0 1 2 3 km
Lineation
Fold axis, measured
Pole of bedding plane
Fold axis, constructed

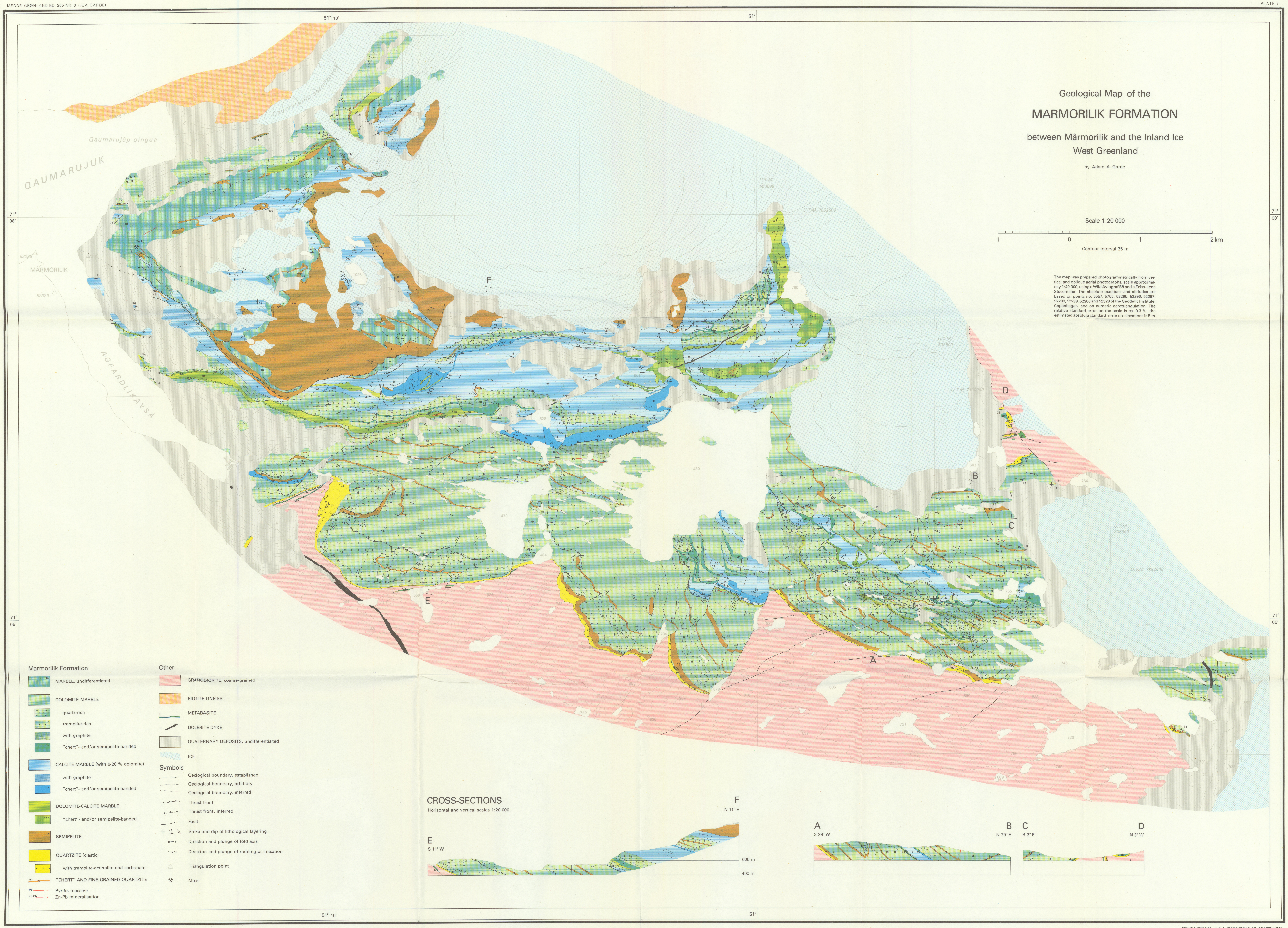


Legend see Plate 6

⇒ Mineralised horizon
∘ Marble with graphite

tr.: trace
d.l.: detection limit (Zn<5, Pb<2, Cu<3, Ni 3 ppm)


GENERAL STRATIGRAPHY AND CORRELATION
OF THE MARMORILIK FORMATION
EAST OF MÂRMORILIK
Index map
0 1 2 3 km
Marmorilik Formation
GRANODIORITE
INLAND ICE
QUATERNARY DEPOSITS
Cross-sections
Scale 1:20 000
0 1 2 km
DOLOMITE MARBLE
with graphite
"chert"- and/or semipelite-banded
CALCITE MARBLE
"chert"- and/or semipelite-banded
DOLOMITE-CALCITE MARBLE
"chert"- and/or semipelite-banded
Quartz-rich marble
Tremolite-rich marble
SEMIPELITE
QUARTZITE
GRANODIORITE basement
Stratigraphic columns a-a to h-h
Lateral distances approximately true along strike
Generalised
stratigraphic
column
2 km
1
0
Scale 1:20 000



Kartografi: Jack E. T. Larsen.

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