GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT NR. 9

The Geological Survey of Greenland
Report no. 9

Some border relations between supracrustal and infracrustal rocks in South-West Greenland

by

B. F. Windley, N. Henriksen, A. K. Higgins,
E. Bondesen and S. B. Jensen

KØBENHAVN 1966

SOME BORDER RELATIONS BETWEEN SUPRACRUSTAL AND INFRACRUSTAL ROCKS IN SOUTH-WEST GREENLAND

by

B. F. WINDLEY, N. HENRIKSEN, A. K. HIGGINS,
E. BONDESEN AND S. B. JENSEN

With 10 figures and 1 map

1966

Statens trykningskontor
In 14-109

CONTENTS

Abstract

Three types of border relation between supracrustal and infracrustal rocks are described from South-West Greenland. In the Ravns Storø area a largely volcanic series, possibly equivalent in age to the Tartoq Group, passes downwards into the underlying gneisses via a transitional migmatite front. The supracrustal bedding passes conformably downwards into the gneissic foliation and there is a progressive downward increase in metamorphic grade and degree of mineral orientation.

In the northern part of the Ivigtut region Ketilidian supracrustals lie with a major unconformity on pre-Ketilidian gneisses and (Tartoq Group) supracrustals, between which there is a migmatite front relation. Passing southwards the autochthonous unconformity between the Ketilidian supracrustals and the underlying rocks is affected by a series of progressive tectonic modifications. Faulting parallel to the axial planes of Ketilidian second phase folds in the supracrustals is followed by thrusting along the unconformity, giving rise to a parautochthonous border, which further south passes into an allochthonous border modified by gneissification and associated with the formation of granitic rocks. Earlier basic dykes together with the gneissic foliation are dragged along the transitional border which simulates a transition zone between a supérstructure and an infrastructure. In association with this increase in tectonisation there is a concomitant increase in grade of metamorphism of the supracrustal rocks from an almost unmetamorphosed state through greenschist facies and epidote-amphibolite facies to amphibolite facies.

I INTRODUCTION

a) Background and scope of the study

The study of the contact relations between supracrustal rocks and adjacent infracrustal gneisses has received relatively little attention amongst geologists compared with the study of the rocks themselves. Before further elaboration on this subject the following definitions are given:

The term "supracrustal" is used by the writers to include all forms of sedimentary and volcanic rocks which are sufficiently untransformed for them to be recognisable as such. The term "infracrustal" is used to denote all gneissified, migmatised and granitised rocks and may comprise any or all of the following: a) the old gneissic basement on which supracrustal rocks have been deposited, b) reactivated gneissic basement, and c) gneissic rocks derived by migmatisition of supracrustals.

The following three types of contacts between supracrustal and infracrustal rocks have been described from various fold belts:

1) A sedimentary contact is that most commonly found between supracrustal rocks and underlying gneisses. A cover-basement contact, which is mostly unconformable to the structure of the underlying rocks, occurs for example, between Torridonian and Lewisian rocks in north-west Scotland (Ramsay, 1958 and 1963), between Cambrian and Precambrian rocks in north-west Wales (Shackleton, 1953), between Gardar and Ketilidian-Sanerutian rocks in south Greenland (Poulsen, 1964), and between Ketilidian and pre-Ketilidian rocks in south-west Greenland (Higgins and Bondesen, 1966, and section IIc of this report). It is also possible for sedimentary rocks to be deposited conformably on earlier horizontal gneisses, e.g. the Cambrian metasediments on Precambrian gneisses in the Trondheim region, central Norwegian Caledonides (Oftedahl, 1964).

2) A migmatite front may separate supracrustal and infracrustal rocks. Wegmann (1935) described the rocks in this situation as belonging to two stockwerke - a superstructure and an infrastructure. Well known examples of this feature have been recorded from the Svecofennian fold belt in the Pellinge area of south-west Finland (Sederholm, 1923; Wegmann and Kranck, 1931), from the Caledonian fold belt in north-east Greenland (Haller, 1955),

and from the Variscan fold belt in the central Pyrenees (Zwart, 1963). A migmatite front appears to be a relatively rare feature at the present level of exposure of the crust.

3) A tectonic contact between the two rock groups may result from later deformation of either of the above two types of contact. To the writers' knowledge no examples have been recorded of a tectonised migmatite front, but a deformed cover-basement contact is well known. Ramsay (1958 and 1963) has described such a tectonic contact between the Moinian and Lewisian rocks at Glenelg and Loch Hourn, north-west Scotland, where an original unconformable relationship between the two groups has been almost completely obliterated by the first phase of isoclinal folding of the Moinian rocks.

The deformation along a cover-basement contact may be spatially and genetically associated with metamorphism and in advanced stages with granitisation, mobilisation and reactivation. These processes can mutually assist in the blurring and eventual obliteration of an originally unconformable contact between the two rock groups. A mobilisation of the gneisses along the contact zone may locally give rise to intrusive relations with the supracrustal rocks, and a reactivation of the gneisses along the contact may produce a thermal aureole of high temperature minerals in the overlying cover rocks. Such a reactivated cover-basement contact appears to exist in the Umanak district of west Greenland (G. Henderson and T. C. R. Pulvertaft, pers. comm.).

The purpose of the present paper is to describe examples of, and the relations between, the three types of contacts from a part of south-west Greenland (fig. 1). Elucidation of the type of border relationship between supracrustal and infracrustal rocks can provide important evidence bearing on the mode of early development of a fold belt. The study of such relations in south-west Greenland has shown that the supracrustal rocks can be divided into two groups of different ages: one separated from the underlying gneisses by a migmatite front and the other by an unconformity. Where this unconformity was obliterated by later deformation, a conformable tectonic border was produced. High grade metamorphism of the supracrustals and granitisation were associated with the most advanced stages of tectonisation.

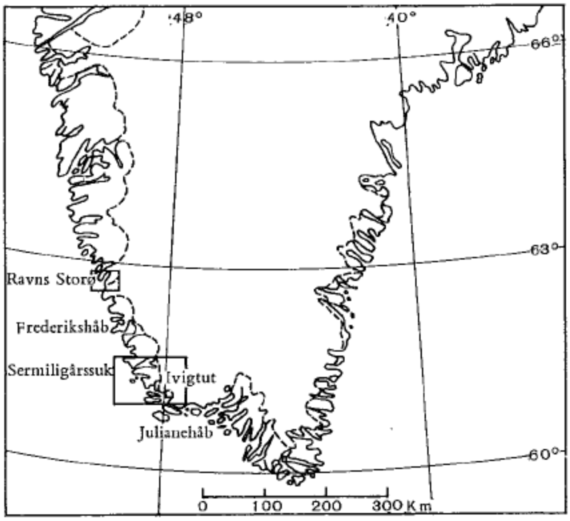


Fig. 1. Index-map showing location of the area described.

b) Regional geological setting

The broad chronology of south Greenland is as follows:

Post-Gardar	Intrusion of basic dykes
Gardar	Sedimentation and alkaline igneous activity
Sanerutian	Reactivation under plutonic conditions
Kuanitic	Intrusion of basic dykes
Ketilidian	Sedimentation, plutonism and orogenic deformation
	Intrusion of basic dykes
Pre-Ketilidian	Sedimentation, plutonism and orogenic deformation

Higgins and Bondesen (1966) have described the supracrustals and gneisses beneath the Ketilidian unconformity in Midternæs and Grænseland. The supracrustals in the Tartoq-Sermiligârssuk-Midternæs area have been defined collectively as the Tartoq Group (the greenschists of this report); supracrustals possibly equivalent in age to the Tartoq Group occur in the Ravns Storø area. Gneisses, some of which are transformed derivatives of the Tartoq Group, mostly form the floor of deposition of the Ketilidian supracrustals of Midternæs and Grænseland.

The Ketilidian sedimentational phase in the Ivigtut region is here defined from the Midternæs and Grænseland supracrustal deposits and the metamorphism and reconstitution of these rocks to a series of gneisses is defined as the Ketilidian plutonic phase (Berthelsen and Noe-Nygaard, 1965). Such gneisses are found with certainty in the Sánerut area (see this report) and in the Ilordleq area just south of Sánerut (Watterson, 1965) and they probably continue on the south-eastern side of the Julianehåb district.

In the Julianehåb district to the south-east of the Ivigtut region the effects of the Sanerutian reactivation are most apparent and have obscured the relations of the earlier rocks (Allaart, 1964, p. 9 and in press).

Where they are involved in a later deformation, discordant amphibolite dykes are important both chronologically and structurally. This deformation can give rise to a tectonic border between, and parallel foliations in, adjoining supracrustal and infracrustal rocks. Ramsay (1963) has shown how the discordant amphibolite dykes of the Lewisian become progressively conformable to the foliation as the angular unconformity between the Lewisian and Moinian (Torridonian) rocks is eliminated. In south Greenland three periods of amphibolite dyke emplacement have so far been distinguished (Watterson, 1965; Allaart, in press). The 1st period dykes occur in the Ketilidian essentially between the sedimentational and plutonic phases, the 2nd period dykes were intruded under cratogenic conditions in the Kuanitic period of time, and the 3rd period dykes were emplaced under plutonic conditions in the Sanerutian. Some relations between amphibolite dykes of different ages and the borders between the supracrustal and infracrustal rocks will be described and discussed below.

II REGIONAL DESCRIPTION

a) Some border relations near Ravns Storø

To the east of Ravns Storø there is a zone of supracrustal rocks between 1 and 2.5 km wide extending for about 17 km in a north-easterly direction (fig. 2). The supracrustal rocks, which are downfolded in a syncline, consist of metavolcanics with thin quartzites and schists and they contain bodies of metagabbro. The conformable border between the supracrustals and the underlying gneisses is transitional and is interpreted as a migmatite front.

i) The supracrustal series

Metavolcanics of various types comprise the greater part of the supracrustal succession which is between 1 and 2 km thick. The metavolcanics vary rapidly in type across the strike from undeformed pillow lavas, to slaty or compact hornblende schists, beds of hornblende "garbenschiefer" and hornblende-epidote metalava. Individual beds range up to 30 m wide. Amygdules in the metalavas increase in size gradually upwards within a single unit indicating that the beds are the right way up.

The metavolcanics have an actinolitic hornblende-epidote-calcite-quartz-albite-chlorite-garnet assemblage corresponding to the epidote-amphibolite facies.

Quartzites occur locally as thin beds up to 6 m wide and chlorite schists and talc schists in beds up to 10 m wide.

The supracrustal rocks appear to have undergone surprisingly little deformation; only a few minor folds can be seen, confined to incompetent beds, when traversing the whole outcrop of the series.

ii) The migmatite front

The metavolcanics grade downwards into the underlying gneisses through a transition zone which is interpreted as a migmatite front. The border between the two rock groups has the following features:

The transition zone is in the form of an increasing number of gneissic layers in the metavolcanics as the gneisses are approached, thus within the zone there is an intense intercalation of the two rock types (fig. 3). Individual basic and gneissic layers reach up to several metres in width. The width of the zone varies between 25 and 100 m; nowhere has a sharp contact

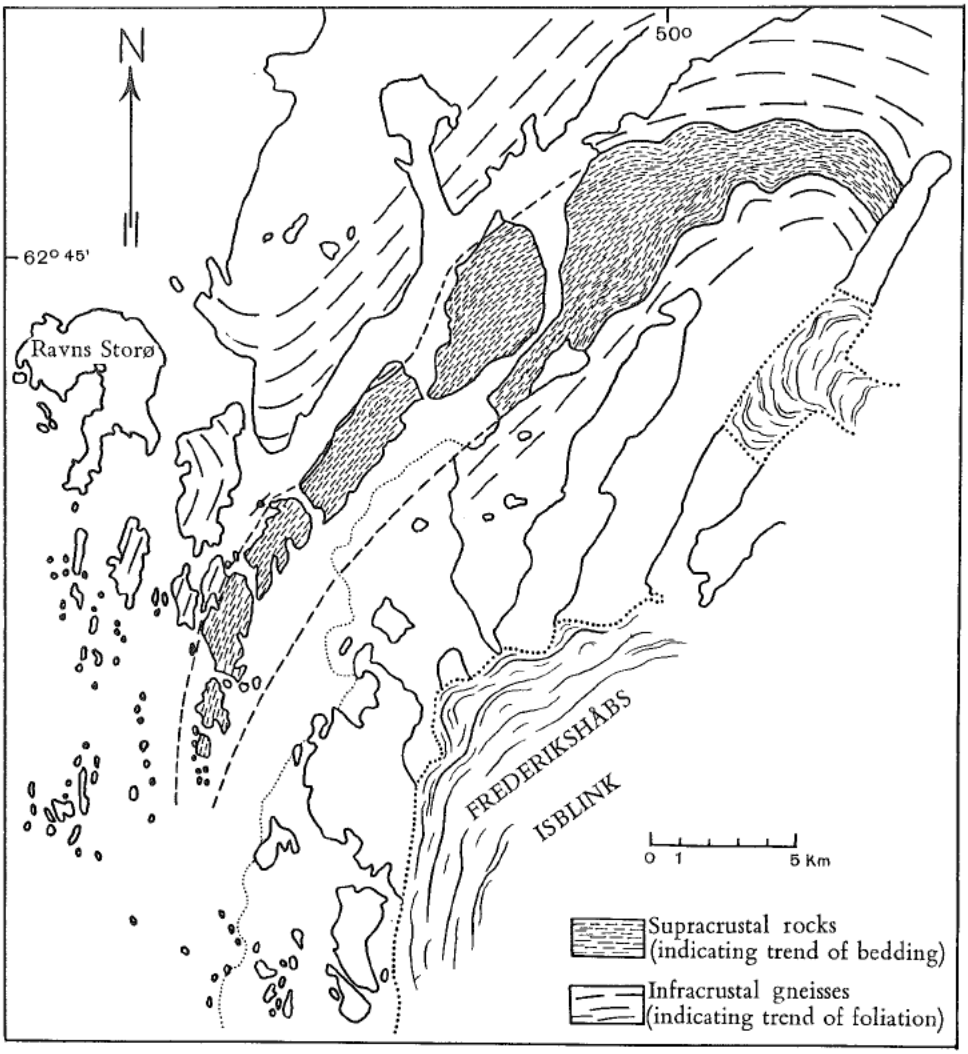


Fig. 2. Geological sketch map of the Ravns Storø area.

been seen between the two rock groups which could be regarded as of sedimentary or tectonic origin. The bedding of the metavolcanics is conformable to that of the intercalated layers in the transition zone and to the foliation of the underlying gneisses on both sides of the outcrop of the supracrustal series (i. e. on the limbs of the syncline). No folds have been seen within the transition zone.

There is an increase in metamorphic grade passing downwards through the transition zone. The metavolcanics have actinolitic hornblende, epidote, calcite, quartz, chlorite and albite as essential minerals. Passing downwards in the transition zone the basic layers become more amphibolitic, so that the lowermost layers consist only of hornblende and an intermediate plagioclase, the metamorphic grade of which (amphibolite facies) corresponds to that of the underlying gneisses.

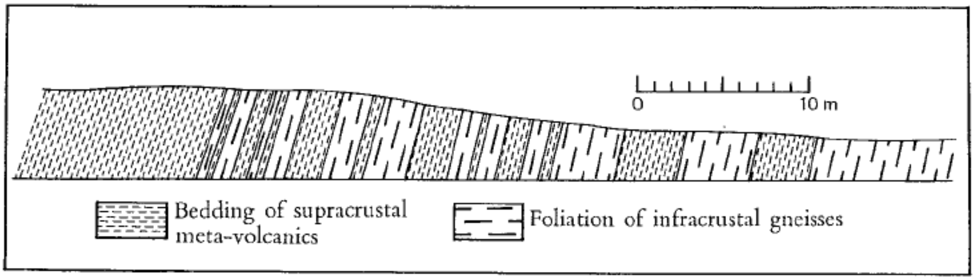


Fig. 3. Diagrammatic representation of the migmatite front on the north side of the Ravns Storø succession. Drawn from a photograph. Looking south-west.

Accompanying the increase in grade in metamorphism there is a downward increase in the tectonisation of the layers in the transition zone. In the metavolcanics bedding is marked a) by the intercalation of the various rock types (e.g. pillow lavas, quartzites, etc.), and b) by the cm-scale layering of the metavolcanics. Passing downwards through the transition zone this supracrustal bedding gives way to a foliation in the more amphibolitic layers and in the intercalated gneissic layers which passes downwards into the regional gneiss foliation.

In association with this passage from bedding to foliation there is a downward increase in the degree of orientation of the constituent minerals. Whereas in the metavolcanics hornblende has a moderately preferred orientation (in garbenschiefer beds it has only a weak alignment), in the amphibolitic layers lowermost in the transition zone it has a strongly preferred orientation, giving rise to a marked linear fabric. This lineation is parallel to that in the underlying gneisses and included amphibolitic lenses and layers.

In the metavolcanics there are quartz veins and lenses up to 2 m in length trending E-W. In the gneisses there are several generations of pegmatites. Conformable replacement pegmatites are cut by discordant pegmatite dykes up to 2 m wide trending NE and NW; none of these pass into the transition zone or into the supracrustal rocks. The supracrustal rocks contain no evidence of granitisation or migmatisation; they are cut by neither granitic veins nor pegmatites.

Although it is well appreciated that a conformable transitional border zone between supracrustals and gneisses can be derived by deformation and gneissification of an original unconformity (see p. 24), it is considered that the features of the border zone described above lead most reasonably to the conclusion that it is a front of migmatisation. Its transitional and conformable nature for 17 km along the strike, the lack of deformation features in the supracrustals within and immediately above the border zone, together with the downward increase in metamorphism and tectonisation and the gradual downward passage of bedding into foliation afford evidence of its origin as a migmatite front.

iii) The gneisses

The rocks immediately below the migmatite front consist of a monotonous series of granodioritic to quartz-dioritic gneisses with little or no stratigraphic variation. Homogeneous gneisses predominate; banded and veined gneisses are developed locally. The gneisses, which have the primary mineral assemblage hornblende-biotite-oligoclase-microcline-quartz-(garnet) with secondary muscovite-epidote-chlorite, crystallised under amphibolite facies conditions. The gneisses contain layers and lenses of amphibolitic material which were probably derived from the earlier meta-volcanic succession.

iv) Deformation features

In the incompetent beds of the supracrustal series (hornblende, talc and chlorite schists) there are a few minor folds plunging shallowly to the north-east, with wavelengths up to 30 cm and amplitudes up to 40 cm and with steep to vertical axial planes parallel to which there is a strain-slip cleavage.

In the gneisses there are relict intrafolial folds plunging shallowly to the NE and SW with amplitudes and wavelengths of 10-40 cm and with SE- or NW-dipping axial planes. The folds have a strong axial plane structure S_1, in the form of a gneiss foliation which represents an incipient stage in the development of the regional gneiss foliation, S_1. Fold limbs are truncated by S_1 and many folds occur as tectonic inclusions in the gneisses. All stages are present showing the formation of the regional gneiss foliation as a transposition foliation from an axial plane structure to the intrafolial folds. As the folds in the supracrustal and gneissic rocks have similar axial orientations and strong axial planar recrystallisation fabrics, it is considered that they both formed during the first folding phase in the rocks above and below the migmatite front. A similar conclusion was reached by Zwart (1963) for the development of the first phase folds above and below the Variscan migmatite front in the Central Pyrenees. The development of the regional gneiss foliation from the first phase "drag" folds probably took place during the formation of the migmatite front. It is significant that the gneiss foliation developed parallel to the bedding of the supracrustal series as a tectonic feature and not as the product of simple mimetic recrystallisation of bedding.

The supracrustal series, occurring in a syncline, has been folded together with both the migmatite front and the gneisses, by a late phase of the first deformation or by a second fold period with a NE-SW trend and vertical axial plane. The supracrustal rocks have been preserved on account of their presence in the core of this downfolded structure.

b) Tartoq Group greenschist areas in the Sermiligârssuk region

In the Sermiligârssuk region there occur a number of related greenschist areas. The greenschists are rather homogeneous, can be rather massive, and contain local bands of talc schist, quartz schist and pelitic schists, and bodies of metagabbro. Relict pillow structures can be seen locally. The greenschists may be regarded as a succession of sedimentary and volcanic rocks with sill-like intrusions which have been folded and metamorphosed under mainly epidote-amphibolite facies conditions.

The greenschist areas are surrounded by infracrustal granodioritic to quartz-dioritic gneisses which, in contrast to the greenschists, contain numerous leucocratic veins and pegmatites and may be described as migmatites.

The border relations between the supracrustal greenschists and the infracrustal gneisses are somewhat variable in different areas, and in places the original relations have been partly obliterated by later deformation.

Probably the greenschists were originally a single connected superstructure, but subsequent isoclinal folding and faulting, and later erosion, have left them preserved as synclinal or fault-bounded wedges within the infrastructure. The greenschists found today in the areas north and south of Sermiligârssuk fjord, and on Midternæs, comprise collectively the Tartoq Group.

i) Midternæs

Greenschists occur on Midternæs in two zones: a narrow western zone, and a broader eastern zone. The western zone is a continuation of the narrow zones described by Ayrton (1963) south of Sermiligârssuk fjord, and the eastern zone can probably be correlated with that described by Weidmann (1964) south of Sioralik fjord.

The greenschist-gneiss boundaries on Midternæs are in some places sharp and in others gradational. The south-east boundary of the eastern schist zone is sharp and is probably a structural contact, although it is parallel to the foliation in both schists and gneisses. Both boundaries of the western zone and the north-west boundary of the eastern zone are gradational.

The three gradational boundaries are all similar. The transition from schist to gneiss takes place over a distance of from 30 to 250 m perpendicular to the strike, in each case an increasing proportion of leucocratic gneissic veins being encountered such that there is a gradual passage into banded chlorite or hornblende gneisses. The gneissic veins are usually concordantly intercalated within the schists of the border zone, and the border zone itself is parallel or sub-parallel to the regional foliation of both schists and gneisses.

The rapid alternations of schist and gneissic veins may give the outcrops in the border zone a conspicuous banded appearance. This is particularly well seen in the southern border zone of the western schist band in the cliff exposures on the north side of Sioralik fjord.

The gradational border zones are interpreted as fronts of migmatisation. Within the infracrustal gneisses of much of Midternæs thin bands, lenses and schlieren of hornblende schist, amphibolite, talc-bearing rocks and calcareous schists may be encountered. These remnants suggest that much of the gneisses of Midternæs were derived from a rock sequence comparable to that now found in the supracrustal schist zones.

ii) The areas on the north side of Sermiligârssuk fjord

To the north of Sermiligârssuk fjord two greenschist areas are found, both of which have migmatitic border relations with the surrounding gneisses.

1) The western area: Thrusts or faults have been superimposed along most of the border zone of the western greenschist area. However, original undisturbed migmatitic contacts can be observed in places.

In the migmatitic border zones it can be seen that the migmatisation has led not only to transection of the greenschists by leucocratic veins and pegmatites, but to a diffuse "gneissification" and "quartz-dioritisation" which can be seen to have gradually transformed the greenschists into quartz-dioritic gneisses. The metasome in this process is mainly quartz, but alkalis are also of importance.

The intensity of the quartz-dioritisation varies and greenschist schlieren within a small area can be altered to a very variable extent. A further expression of such variability is seen in the width of the migmatisation zone. In some areas the gradual transition takes place over a distance of about 500 m, in other areas over a zone 5-10 m wide, and even examples of knife-sharp contacts are known.

As the thrusts found along much of the border zone traverse rocks of different degrees of migmatisation, they are believed to cut through different niveaux of migmatisation and are therefore assumed to be post-migmatitic. However, they are related to the structural inhomogeneity between infra- and superstructure.

The combination of border relations with and without thrust superimposition suggests that the thrusts have only a small displacement.

2) The eastern area: The eastern greenschist area is bordered towards the north mostly by later thrusts and faults, but its western border can be regarded as a transitional migmatite front although minor thrusts and shear zones are locally present.

The "in situ" border relationships are sometimes characterised by a leucocratic veining of the greenschists, but more often by a diffuse transitional gneissification of the greenschists. The border is in some places gradational, but may also be knife-sharp. The traces of gneissification can be seen in the greenschists up to 100 m from the gneisses as slightly more leucocratic material in the darker unaltered greenschists. The proportion of these more leucocratic schlieren increases towards the border of the greenschists and in a zone near the border small porphyroblasts are often developed.

The gneisses between the eastern and western areas: A large gneiss area of veined and streaky amphibole and biotite gneisses of granodiorite to quartz-diorite composition occurs between the two greenschist areas. These gneisses contain schlieren or lenses of relict greenschist elements which have been more or less transformed; in some localities the structural relationships between the gneiss and the schist enclaves are almost agmatitic.

The relict greenschist elements are variable in form. Where least transformed, they occur as non-gneissified greenschist schlieren and lenses in the gneisses, but where most transformed, they occur as dark gneissic lenses which can only be recognised as having originally been greenschists because all stages of transition are represented.

In this particular gneiss area the degree of transformation of the greenschist relics varies from place to place, and it is clear that the rocks have been influenced by different intensities of migmatisation and gneissification. In the south-west part of the area, near Sermiligârssuk, the greenschist relics occur in an agmatitic zone that is transected by migmatising gneissic pegmatites. In other parts of the area a varied degree of gneissification of the greenschist elements occurs in addition to pegmatisation.

The occurrence of the many greenschist relics between the two supracrustal greenschist areas suggests that most of this gneiss area has been formed by migmatisation and gneissification of rock types similar to those preserved in the bordering greenschist areas.

iii) The areas on the south side of Sermiligârssuk fjord

Several Tartoq Group greenschist areas related to those already described occur on the south side of Sermiligârssuk and Sioralik fjords.

The eastern areas have been investigated by Ayrton (1963) and Weidmann (1964), and in both cases the junctions between greenschists and gneisses have been described as migmatitic, often with the development of an agmatitic border zone.

The Tartoq area has been described by Jacobsen (1961). The greenschists here are weakly altered and relict pillow-structures may occasionally be seen. The greenschists are gradually transformed westwards, first into quartz-dioritic greenschists, and then into gneisses, the transition being completely gradual over a zone from 200 m to 1 km wide. The alteration from greenschist to gneiss is, according to Jacobsen, caused by a sporadic addition of mainly SiO_2 and smaller amounts of Na_2O and K_2O, with a relative decrease of FeO, MgO and CaO. The front of the quartz-dioritisation agents, the metasome front, is described as cutting the foliation in the greenschists obliquely in the northern part of the area, and as conformable to the foliation planes in the south. The border of the quartz-dioritic greenschists with the gneisses also follows the foliation planes, except in the north where the border is formed by a later thrust plane.

The eastern border of the Tartoq greenschists is bounded by a narrow zone of quartz-diorite gneisses which have the same appearance as many of the gneissified greenschists in other parts of the Sermiligârssuk region. The actual gneiss-greenschist border line is often knife-sharp, where it appears that the quartz-dioritisation was halted abruptly along specific foliation planes.

c) Ketilidian border relations in the Sermiligârssuk-Ivigtut region

Ketilidian supracrustal rocks can be traced in an almost continuous belt from Midternæs, through Grænseland to Qôrnoq, to the island of Sánerut and to the islands of Arsuk Ø and Storø (Map 1).

The most complete succession known is in Midternæs and Grænseland where it may be divided into two groups: the lower mainly sedimentary Vallen Group, and the upper mainly volcanic Sortis Group. The earliest sedimentation of the Vallen Group in these two areas took place in shallow basins on a peneplained gneiss surface, and was influenced by contemporaneous faulting.

Two main Ketilidian phases of deformation affect the succession: an early phase of overturned tight to isoclinal folds developed with flat-lying axial planes, and a later open to tight folding with NE-trending near-vertical axial planes.

The grade of metamorphism of the Ketilidian rocks increases from north to south, and in the region under consideration is highest in the Sánerut area.

The nature of the border relations between the supracrustals and the gneisses changes southwards from an autochthonous simple unconformity, via a parautochthonous relationship, to an allochthonous border modified by granitisation and migmatisation.

i) Midternæs and north Grænseland

The Ketilidian rocks of Midternæs and north Grænseland rest unconformably on pre-Ketilidian gneisses and greenschists. For the most part the unconformity appears to be an original autochthonous feature.

In north-east Midternæs the lower part of the Vallen Group is not represented, and was probably not deposited. Greywackes and semi-pelites of the middle Vallen Group rest on quartzose gneiss and banded hornblende gneiss, the plane of unconformity transecting pegmatite veins in the gneiss.

In western Midternæs quartzites and the basal conglomerate of the lower Vallen Group rest on an uneven surface of Tartoq Group schists (fig. 4). The conglomerate is locally 4 m thick and its components are angular to sub-rounded pebbles of quartz and quartzose gneiss. The conglomerate is badly sorted, for the most part non-bedded, and may have been a residual gravel accumulation on the sub-Ketilidian gneiss surface. All the pebbles could have been derived locally by erosion of the gneiss.

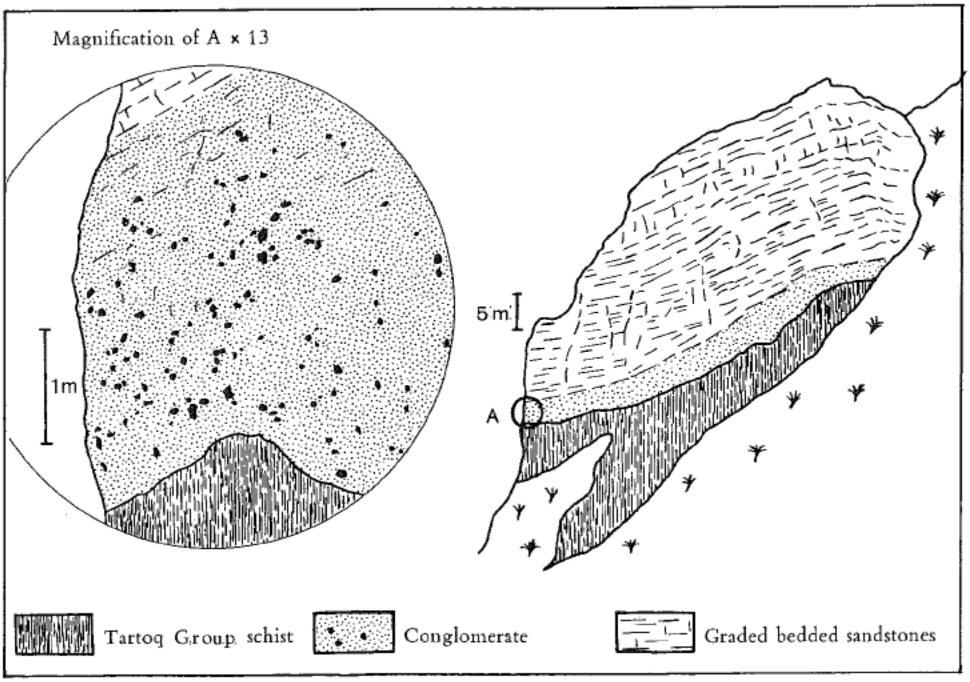


Fig. 4. Basal Ketilidian conglomerate resting on an uneven surface of steeply inclined Tartoqian schists in NW Midternæs. Drawn from photographs.

A thick well bedded quartzite sequence up to 150 m thick rests on the gneisses in south-east Midternæs. At one locality the quartzites at the base of the sequence appear to fill in minor irregularities in the gneiss surface. At a few other localities there are indications of slight movements along the plane of unconformity, but these appear to be of minor significance.

In the northern part of north Grænseland the same thick quartzite sequence occurs, but southwards higher stratigraphic levels of the Vallen Group rest on the sub-Ketilidian gneiss surface representing the deposits successively laid down in a transgressing sedimentary basin. In the south part of north Grænseland calcareous sediments rest on a thin conglomerate of quartzite boulders.

The early Ketilidian deformation produced major and minor isoclinal overturned and recumbent folds associated with low angle thrusts in the sediments of the Vallen Group, but these structures only rarely distort the massive basal quartzites. A few sigmoidal structures found in the Tartoq Group greenschists in east Midternæs may be related to this phase, but no equivalent folds have been recorded in the gneisses. In the northern part of north Grænseland shear zones appear to have developed at the gneiss-quartzite border, and just below the border in the gneisses.

The later NE folding produced open to tight folds throughout the Ketilidian succession and, where greenschists underlie the unconformity, both unconformity and greenschists are deformed by several major folds. This NE folding seems to be responsible for the sharp eastward swing of the trace of the unconformity in north Midternæs. Where the unconformity is based on gneisses, these and the basal quartzite are usually deformed by only a few gentle folds. However, in the south part of north Grænseland a 1-2 m altered upper zone of the gneiss overlain by calcareous sediments exhibits good NE folds of this generation because of the incompetency of the altered (weathered) zone.

The supracrustal rocks of Midternæs and north Grænseland are in an almost unmetamorphosed state, or at the most were metamorphosed under very low greenschist facies conditions.

ii) Central Grænseland

In central Grænseland thin beds of arkoses and badly sorted conglomerates were deposited in small basins and depressions on the gneiss surface. The conglomerate pebbles and boulders are mainly of gneissic origin but some are also of quartzite, dolomite and amphibolite. Dolomitic limestones overlie these deposits, or locally rest directly on the gneisses, and are associated with a deep carbonatisation of the underlying gneisses and sediments (fig. 5). The carbonatisation of the gneisses is characterised by alteration of all the minerals (chiefly feldspars), except for quartz which is found "in situ" in the original gneiss fabric. Pegmatites and fold structures can be locally traced. Thick veins of dolomite occur in the pre-existing joint system and at a greater depth in the gneisses carbonatisation has taken place outwards from the joint fissures leaving centrally placed and comparatively unaltered

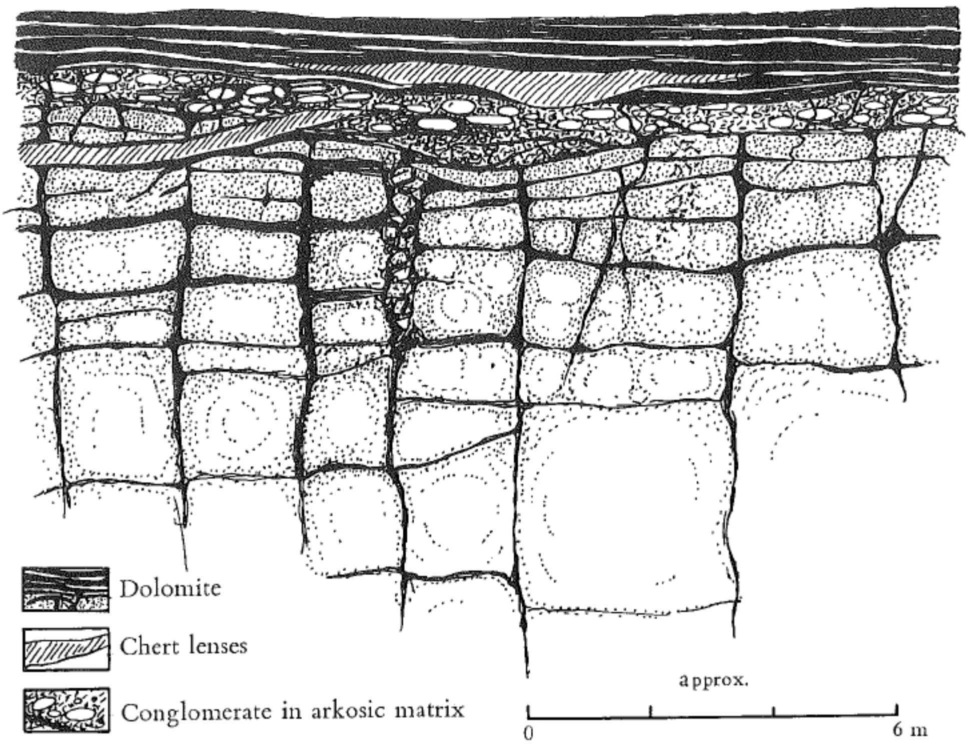


Fig. 5. Schematic section through the carbonatised sub-Ketilidian surface in central Grænseland. Dotting shows the intensity of carbonatisation in the gneiss.

blocks of gneiss. Traces of carbonatisation have been found more than 50 m perpendicularly below the unconformity.

Varved shales with suncracks overlie the dolomites, and are succeeded by a black magnetite sand which also forms the matrix of a 1-8 m thick conglomerate of quartzite boulders (fig. 5). Northwards this conglomerate, with boulders up to 1.5 m in diameter, rests directly on gneisses. Here the gneisses are unaffected by carbonatisation, but in their uppermost part they exhibit a thin zone of alteration which perhaps may be attributed to sub-aerial or aqueous weathering of the sub-Ketilidian surface.

These sediments were deposited in a transgressing sedimentary basin to the south of that which influenced early sedimentation in Midternæs and north Grænseland. The ridge-like area between the two sedimentary basins seems to have been controlled by faults; there is evidence for continued movements in the occurrence of flysch-like sediments in the mid-Vallen Group.

The ridge between the basins was first covered by graded greywackes of the upper Vallen Group.

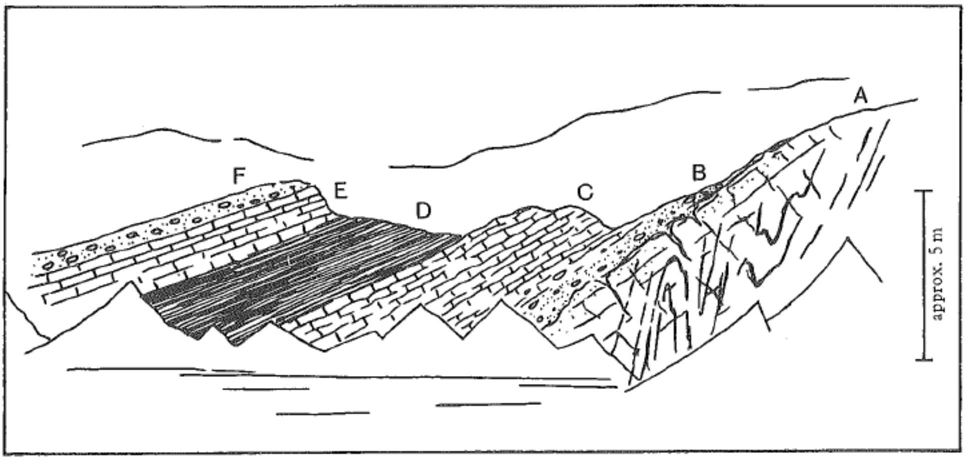


Fig. 6. Section through the lowermost part of the Vallen Group in the south central Grænseland, showing the basal unconformity. A) Pre-Ketilidian gneisses showign fold structures in banded biotite gneiss. B) Basal residual conglomerate (carbonatised). C) Basal dolomite. D) Varved slates. E) Rusty dolomite. F) Ore-conglomerate. Drawn after a field sketch.

The early Ketilidian deformation in central Grænseland led to the formation of large tectonic breccias in the gneisses, and possibly also shearing in the NNW-striking banded amphibolites, although some of these breccias may be of earlier generation as they are parallel to pre-Ketilidian faults. Parallel to the axial planes of the second phase folds there is a set of closely spaced minor faults, the majority of which, with a displacement of a few metres, transect competent quartzites and produce folds in incompetent shales. Others, with displacements up to 100 m, cause strong deformation with NE-trending fold axes in incompetent sediments.

The supracrustal rocks of central Grænseland were subjected to a regional metamorphism corresponding to the low greenschist facies.

iii) South Grænseland

The border relations in south Grænseland are of tectonic nature due to Ketilidian deformation.

The lower Vallen Group sediments have been thrust over the gneisses so that southwards successively higher stratigraphic levels come in contact with the basement gneisses. This might be combined with a transgressive southern border of the sedimentary basin of central Grænseland, but the sedimentary relations are obscured by the movements.

The upper Vallen Group - a distinct formation of carbonaceous graphitic shales, calcareous sediments and quartzites - is based on a thrust which cuts obliquely through the lower Vallen Group, and in the southernmost region this formation rests on basement gneisses.

Along the border the sediments are strongly sheared and exhibit folds which can be related to the first as well as the second phase of the Ketilidian deformations.

The basement gneisses, which are biotite gneisses with bands of amphibolite, exhibit a strong schistosity which intersects the lithological banding and is concentrated in shear zones. The same schistosity is imposed on metamorphosed basic dykes found in this area, and both the schistosity and the dykes are often found to be folded.

Metasomatic activity along the border was restricted to the formation of quartz and quartzo-feldspathic veins, which may be folded, but which are mainly restricted to the planes of schistosity. These veins are also found in the deformed and schistose parts of the dykes.

Metasomatic activity in, and metamorphic reconstitution of the supracrustal rocks of south Grænseland was restricted to the formation of quartz veins and to a regional metamorphism under epidote-amphibolite facies conditions; biotite is present in places.

iv) Arsuk Fjord - Qôrnoq

The area of Ketilidian supracrustal rocks extending from south-east of Arsuk Fjord to Qôrnoq consists of metasediments and metavolcanics and is a continuation of the Grænseland belt north of Arsuk Fjord. To the west it is bordered by gneiss and to the east by a younger augen granite.

The supracrustals can be divided into two units: the western (lower) half consists of metasediments (mica schists, quartzites and marbles). The eastern unit, above the metasediments, comprises hornblende schist with some horizons of dark mica schist; in a few places pillow structures have been recorded in the hornblende schist. The eastern margin of the unit is formed by a thin horizon of conglomerate which forms a reliable stratigraphic horizon north of the head of Qôrnoq, although at some localities it has been destroyed by the younger augen granite.

Folding and metamorphism of the supracrustals have been more intense than in Grænseland. Thin horizons of quartzites and marble in the metasediments have been disrupted into lenses. The metamorphic grade can be deduced from thin horizons of staurolite-garnet-mica schists which are found in both units; these rocks were recrystallised under conditions of the high epidote-amphibolite to low amphibolite facies.

The boundary between the metasediments and the gneisses can be followed for about 20 km from the inland ice to Qôrnoq. Nowhere is a primary discordant contact between a gneissic basement and a younger series comparable to that described from Midternæs and Grænseland to be seen. Later movements and metamorphism have destroyed the primary contact relations and have formed a transition zone from a few metres up to 400 m wide which, in the field, was termed a "gneissic schist" because it bore both gneissic and mica schist elements in addition to lenses of marble and quartzites.

Small islands in Qôrnoq consist of metasediments which are the continuation of the supracrustal belt, and on Kînâlik peninsula east of Qôrnoq there occur metasediments, an amphibolitic hornblende schist and a conglomerate horizon, which are flanked by a younger augen granite (the same complex as previously mentioned) and a younger homogeneous migmatitic granite. No gneiss is seen at Kînâlik; the locality is mentioned here only because it enables one to trace the Arsuk Fjord - Qôrnoq belt further south to the belt along the south coast of Sánerut island, from Qipisarqo at the eastern end towards the southwest corner of Sánerut. From here the belt may continue to the islands of Storø and Arsuk Ø.

v) Sánerut

The belt of supracrustals along the south coast of Sánerut is best developed at Qipisarqo. The lowest part consists of quartzites overlain by a mica schist horizon and a hornblende schist with pillow structures. Above these occurs a conglomeratic schist and then a thick series of mica schists and semi-pelitic schists. The hornblende schist with pillow structures and the conglomerate form reliable marker horizons for the supracrustal belt. There are a few deviations from the succession outlined which are probably of primary origin: the lower mica schist horizon is missing south-west of Qipisarqo, but the quartzite directly beneath the pillow horizon contains thin mica schist layers; the pillow horizon is missing in the western end of the belt (a small island at the south-west corner of Sánerut) where the conglomerate rests on mica schist. Numerous pegmatite and granite veins cut the mica schist above the conglomerate south of Borgs Havn, but the origin and age of this pegmatite-granite material cannot be elucidated because the southward continuation of the sequence is covered by the sea.

The conglomerate horizon in Sánerut is probably the same as that at Kînâlik and that north of the head of Qôrnoq which lies on top of the hornblende schist and is destroyed by a younger augen granite. If this correlation is correct, then the highest part of the Ketilidian supracrustals in the Ivigtut region is found at Qipisarqo. Berthelsen and Noe-Nygaard (1965) came to a similar conclusion and have defined the conglomerate and the schists above it as a separate group, the "Qipisarqo group".

Deformation of the supracrustal series has been rather intense as is most clearly seen in the pillow horizon and the conglomerate; the pillows and pebbles have been flattened so that the way up of the beds cannot be determined and the pillow structures have been almost completely destroyed south of Qipisarqo in the core of a flexural fold.

The degree of metamorphism of the supracrustals is of the same order as, or possibly a little higher than, that in the belt north of Qôrnoq. The lower mica schist at Borgs Havn is developed in some areas as a staurolite-garnet-sillimanite-andalusite-tourmaline-mica schist which crystallised under conditions of the amphibolite facies.

The gneisses on Sánerut are streaky or veined, quartz- to granodioritic biotite gneisses. Their original boundaries with the metasediments have been modified or destroyed by the formation of younger granitoid rocks and are nowhere clearly preserved.

At Borgs Havn and to its north there occurs a granitic rock of quartz- to granodioritic composition developed in the cores of three anticlinal folds. Remnants of quartzites and mica schists are found against the structurally controlled granitic rocks and to the east of the folds there is a transition from the granitic rocks into gneisses. In the eastern part of the northern anticline, which has an axial culmination, there are lenses of quartzite in the gneiss.

On the south-eastern part of Sánerut there is porphyroblastic foliated granite of granodioritic to granitic composition partly bordered by quartzite (a possible resister to granitisation), but at one locality it cuts metasediments and is bordered by the pillow horizon. The boundaries between the granite and the gneisses are in some places sharp, but in others somewhat diffuse.

North-west of Borgs Havn there is an extensive development of the porphyroblastic foliated granite which at a few localities (6-8 km north-west of Borgs Havn) contains gneiss remnants and lenses of quartzites and mica schists.

The Borgs Havn granite and the porphyroblastic foliated granites transect the structures of the supracrustals and the gneisses but are not in contact with each other. Their mutual relations can only be inferred from their structural behaviour which is indicative of "mise en place" under syn- to late kinematic conditions, the porphyroblastic granite being active later than the Borgs Havn granite. The three anticlines to which the Borgs Havn granite is confined can be seen in both gneisses and supracrustals, although the granite in some places cuts the structures. The foliation in the rather homogeneous porphyroblastic foliated granite is parallel to that in the gneisses, from which it may be deduced that granitisation was active at the same time as the deformation. The porphyroblasts of microcline are, however, mostly euhedral, unoriented and have grown across the foliation indicating that the granitisation (microclinisation) outlasted the deformation.

On the high western part of Sánerut there is a third granite type which is the youngest granite on the island. It has intrusive contacts with the gneisses and the porphyroblastic foliated granite, but on the south-west point of Sánerut, where it borders on mica schists, the contact is migmatitic and remnants of mica schist are surrounded by irregular granitic to pegmatitic veins.

There is a difference in the major fold pattern between the supracrustal and the gneisses which is revealed to some degree by the variation in trend of the fold axes.

There is a wide but systematic variation in the trend of fold axes in the Qipisarqo area; they plunge to the east in the eastern part, to the south in the central part, and to the south-west in the western part of the area (Berthelsen, Bondesen and Jensen, 1962). In the Borgs Havn area and to its west they plunge WSW to W.

In the gneisses the fold axes plunge ENE to E on eastern Sánerut, with a culmination to the north and north-east of Borgs Havn, so that on western Sánerut they plunge to the west.

The relationship between the infra- and supracrustals in this area is best seen in the northern anticline north of Borgs Havn where lenses of quartzite occur as inclusions in the gneiss. The inclusions occur not far from the belt of supracrustals of which they appear to be remnants. North-west of Borgs Havn in the porphyroblastic foliated granite, there are remnants of gneiss with lenses or layers of quartzite and mica schist which are most probably also remnants of the supracrustal belt; this is supported by the occurrence of a quartzite horizon on the south coast of Sánerut north-west of Borgs Havn, which is a continuation of the lower quartzite horizon in the supracrustals at Borgs Havn.

The conclusion drawn from the above relationships is that there exists, at least in the western part of Sánerut a gneissification of the lower part of the Ketilidian metasediments. No trace remains of an original unconformity and it is thus impossible to estimate directly how much sediment has been gneissified. However, if the main sedimentary development was of the same order of thickness as the belt north of Qôrnoq, it cannot have been much.

vi) The Arsuk Ø area

The Ketilidian supracrustals in the Arsuk Ø area have been mapped by J. Muller. They occur in a basin-like depression, the bedding in the northern, western and southern parts of the area dipping inwards towards the centre of the basin, which was probably once linked to the outcrops of Sánerut.

Contacts with the infracrustal gneisses are only exposed along part of the northern border of the basin and on Ivigtut peninsula. In these areas quartzites form the base of the Ketilidian and the contact with gneiss is strongly tectonised. The border zone in the remainder of the area is water-covered.

On a small island between Arsuk Ø and Storø quartzite and calcareous schists, with unknown limits, are found below the quartzites.

The contact relations in this area appear to be mainly tectonic, perhaps modified by thrusting close to the base of the succession, as a similar quartzite group occurs at or near the base in Midternæs and Grænseland.

The foliation in the gneisses below the supracrustals is more or less conformable to the infracrustal-supracrustal border.

The supracrustal rocks of the Arsuk Ø area were metamorphosed under epidote-amphibolite facies conditions.

d) Basic dykes and their relations to the borders

In the Ravns Storø area no metamorphosed basic dykes have been found which approach or transect the border zone between the supracrustal and infracrustal rocks.

In the southern part of the Frederikshåb district the infrastructure is transected by several generations of metamorphosed basic dykes and in the southernmost part of the Ivigtut region they are disrupted, folded and cut by younger pegmatites. These dykes, which are presumed to have had an original dolerite to olivine dolerite composition, have been described as the "Kuanitic dykes" (Berthelsen, 1960) and were regarded as being of a post-Ketilidian age because they cut the infrastructure which was then regarded as Ketilidian. However, the identification of pre-Ketilidian rocks in the north-east part of the Ivigtut region (Higgins and Bondesen, 1966) now makes it clear that most of the infracrustal rocks, and also some of the supracrustal greenschists in the region, are pre-Ketilidian. With this in mind the age of the above mentioned dykes should be reconsidered, as they could be pre-Ketilidian, Ketilidian or post-Ketilidian, or they may include representatives from all three periods.

The relationships between the dykes and the borders between the infra- and supracrustals are of importance as these relationships could indicate not only age relations, but also the degree of deformation which has taken place along some of the borders.

In the Sermiligârssuk region the borders of the Tartoq Group greenschist areas are found in a limited number of localities to be cut by amphibolitic or metadoleritic dykes. These transgressive dykes can only be traced for a limited distance into the greenschist areas, but they demonstrate that at least some of the dykes post-date the deposition of the Tartoq Group.

In south Grænseland metadolerites are common in the infracrustals, but as they are traced towards the border with the Ketilidian supracrustals they become deflected and often exhibit irregular forms (fig. 7). The dykes are all deflected towards the south in a broad zone near the supracrustal border, the deflections being due to Ketilidian deformation which has modified the border relations in this area. The dykes neither transect the infracrustal-supracrustal border nor are they ever found within the supracrustals.

In central and north Grænseland two thin amphibolite dykes do cut into the lowermost part of the Ketilidian supracrustals, and one of them is deformed by the second phase of folding about NE-trending fold axes. It is therefore a Ketilidian basic dyke, and is possibly equivalent to the oldest period of discordant amphibolites (DA_1) described by Watterson (1965) from the Kobberminebugt area. However, Bondesen (in prep.) also considers the possibility that these dykes could be correlated with the DA_2 dykes on the grounds that the NE-trending phase of deformation in Grænseland may be equivalent to Sanerutian deformation in the Kobberminebugt area.

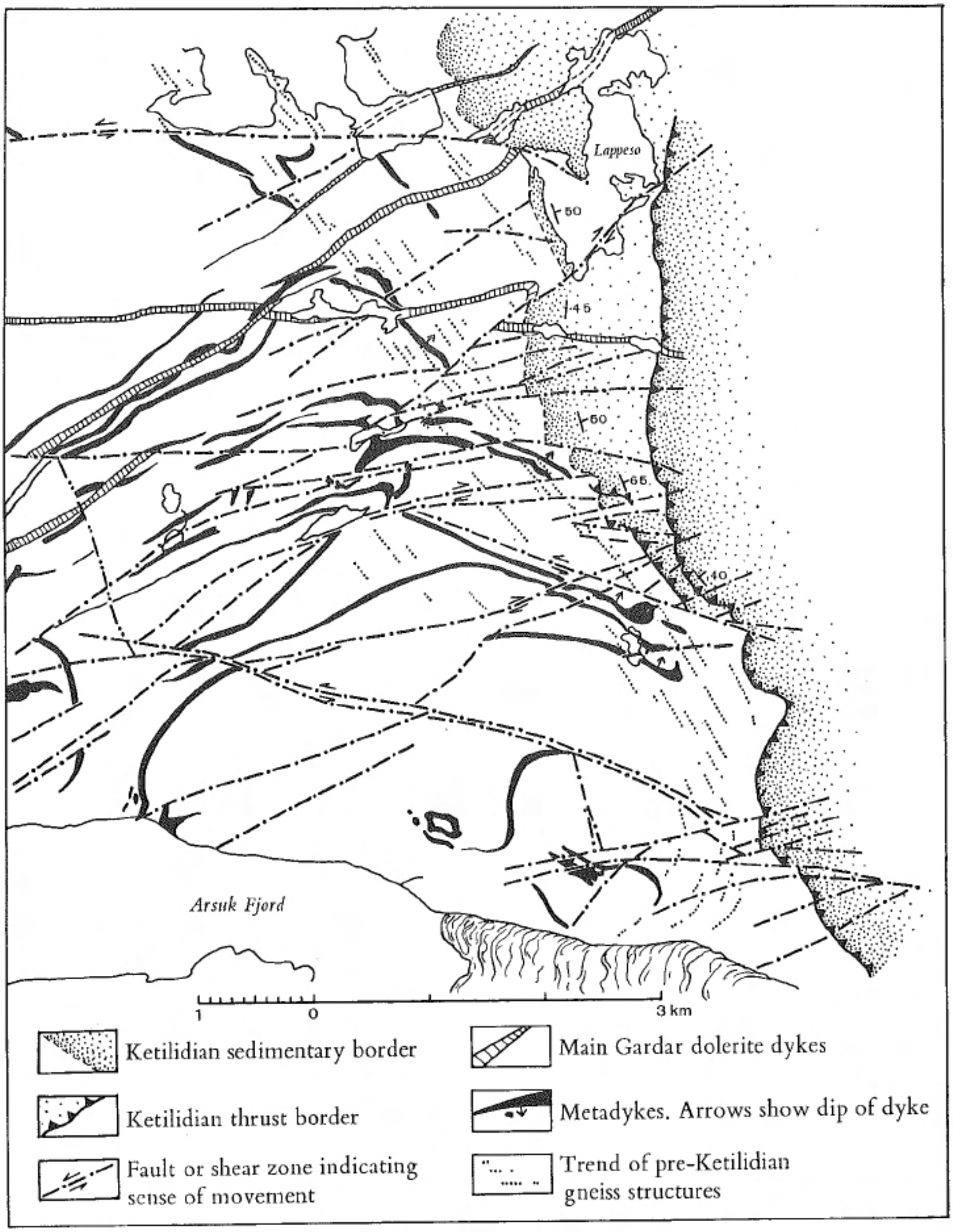


Fig. 7. Map of the south-west part of Grænseland showing relationships of dykes to the Ketilidian supracrustals. Based on the maps of: L. Bonnard (1958), A. Berthelsen (1960) and E. Bondesen (1961).

South of Arsuk Fjord the supracrustal and adjacent infracrustal rocks are more deformed and more highly metamorphosed than further north, as has been described above. In the northern part of this region the metamorphosed dykes which occur in the gneisses still have the character of dykes but have a somewhat irregular trend. The dykes do not cross the boundary between the gneisses and "gneissic schists", the latter probably being gneissified Ketilidian supracrustals. The dykes are often sheared parallel to the gneiss foliation at their contacts. In the southern part of the region the dykes have been still further deformed and metamorphosed, and can only be traced as amphibolite lenses discordant to the gneiss structures.

On Midternæs where the Ketilidian supracrustals rest with a nearly undisturbed depositional contact on pre-Ketilidian rocks, there are unfortunately very few metadolerite dykes. None of these dykes can be shown to cut the Ketilidian rocks, or even to stop abruptly at the unconformity.

With the two exceptions mentioned above, there are no amphibolitic dykes in the infracrustals crossing the boundary into the Ketilidian supracrustals. It is therefore probable that most of the metadolerites or discordant amphibolites ("Kuanitic dykes", Bondesen and Henriksen, 1965) are pre-Ketilidian in age, and not post-Ketilidian as earlier supposed (Berthelsen, 1960).

Bridgwater (1965) regards "the fact that some of the younger 'Kuanitic dyke generations' can be traced for 40 km without folding and without granitisation in the area south of Sermiligârssuk fjord" as supporting the suggestion that these dykes were post-Ketilidian. However in the opinion of the present writers this post-Ketilidian age is not demonstrated by the lack of deformation and granitisation of dykes in this area, as the Ketilidian deformative influence has now been shown to decrease north of Arsuk Fjord. This decrease is clearly exemplified by the conditions in the Ketilidian supracrustal belt along the ice margin.

Post-tectonic dykes of several periods and generations cut the infracrustals and both the Tartoq Group and the Ketilidian supracrustal rocks. The oldest of these is a NW- to WNW-trending swarm of slightly altered basic dykes found along the ice margin in northern Grænseland, Midternæs and north-east of Sermiligârssuk. Later Gardar dykes found throughout the area also cut all the borders, although they sometimes exhibit irregular intrusive features when passing from infracrustals to supracrustals. The latest dykes are coast-parallel swarms of dolerites.

III CONCLUSIONS

Conclusions made above concerning the border relations between the supra- and infracrustal rocks in the different areas are summarised below:

In the Ravns Storø area the transitional and conformable border between the two rock groups is considered to be a front of migmatisation. There is an increase in both regional metamorphism and degree of mineral orientation as the bedding passes into foliation downwards through the migmatite front. The regional gneiss foliation is developed parallel to the migmatite front and to the bedding of the supracrustals, but is a tectonic feature in the form of a transposition foliation parallel to the axial planes of the first phase folds.

The Tartoq Group greenschist areas in the region of Sermiligârssuk have migmatitic border relations with the surrounding gneisses, either in the form of an increasing proportion of gneissic veining in the greenschists as the gneisses are approached, or as a diffuse gneissification brought about by gradual increasing impregnation of the greenschists by salic components. In some places later thrusts and faults have been superimposed on the border zones.

The Ketilidian succession in Midternæs rests unconformably on Tartoq Group greenschists and gneisses which are migmatised derivatives of the Tartoq Group, and in north Grænseland on gneisses which may be partly transformed representatives of the Tartoq Group or the pre-Tartoq Group basement. Locally minor shearing has taken place along the unconformity, or in the gneisses just before it.

In central Grænseland the unconformity has been modified by a deep carbonatisation of the gneiss surface related to dolomite deposition in the lower Vallen Group.

Contacts between the supracrustals and the gneisses in south Grænseland have been modified by thrusting, which is associated with shearing in the gneisses. These effects are related to Ketilidian deformation of this area, which increases in intensity southwards.

In the belt north of Qôrnoq the primary border relations between infra- and supracrustal rocks are obscured by both tectonic and metamorphic transformations. A "gneissic schist" forms the border zone, and there is no discordance between this and the overlying supracrustals and the underlying gneisses. The gneissic schist most probably represents transformed supracrustals, but it may include some reworked gneisses. On Sánerut the corresponding border relations can only be inferred from the Borgs Havn area, where the contact appears to have been gneissified. In both these areas the original discordance between the two groups has been obliterated by intense deformation and metamorphism of Ketilidian age. However, in contrast to the border relations of the Tartoq Group around Sermiligârssuk, in the Qôrnoq - Sánerut belt granitisation has only influenced the supracrustal-infracrustal boundary to a small degree.

In the Arsuk Ø area the border between the supracrustal and infracrustal rocks has been modified by deformation.

The following three types of border relations between supracrustal and infracrustal rocks have been described:

1) A migmatite front relation between supracrustals and gneisses has been established in the Sermiligârssuk and the Ravns Storø areas.

2) An unconformable sedimentary contact exists between Ketilidian supracrustals and Tartoq Group supracrustals and gneisses.

3) A tectonised, metamorphosed and gneissified border was formed in Ketilidian time from type 2.

The Tartoq Group supracrustals (greenschists) around Sermiligârssuk are separated from the gneisses by a migmatite front (fig. 8, b and c) of pre-Ketilidian generation (Higgins and Bondesen, 1966). The supracrustal rocks near Ravns Storø pass downwards into the underlying gneisses via a migmatite front, shown diagrammatically in fig. 8a, which is probably also of pre-Ketilidian age.

The Ketilidian bordeŕ relations are illustrated in figure 9, which shows that a basal unconformity is also preserved in the Midternæs and north Grænseland areas. Passing southwards Ketilidian deformation, metamorphism and granitisation have first modified and eventually obliterated the unconformity (figs. 9 and 10). The varying effects of these modifications are as follows:

In Midternæs and north Grænseland the original unconformity is preserved unmodified apart from local gentle folding (fig. 10a). The first significant tectonic modifications to appear are found in central Grænseland in the form of faults oriented perpendicular to the still autochthonous border and parallel to the axial planes of the second phase folds in the supracrustals

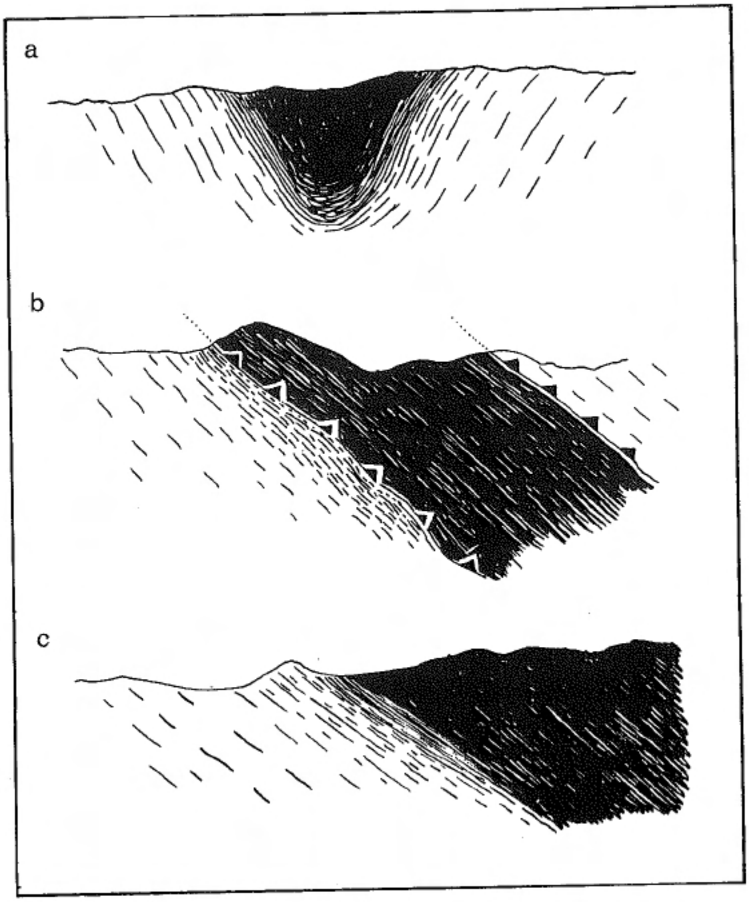


Fig. 8. Diagrammatic representation of different gneiss - greenschist (supracrustal) relationships. a) Ravns Storø. Synformal metavolcanics with gradational migmatitic borders. b) Sermiligârssuk region. Migmatitic borders modified by later thrusts. c) Sermiligârssuk region. Diffuse gneissification of greenschists.

(fig. 10b). In south Grænseland there was shearing and thrusting along the border (fig. 10c) representing the initial development of an allochthonous border zone (parautochthonous), whilst further south, where the border relations are entirely allochthonous, the underlying structures have taken up a position more or less conformable to the border. In the belt between Arsuk Fjord and Qôrnoq the border itself seems to be folded (fig. 10d) and the border relations have been obscured by gneissification giving rise to a

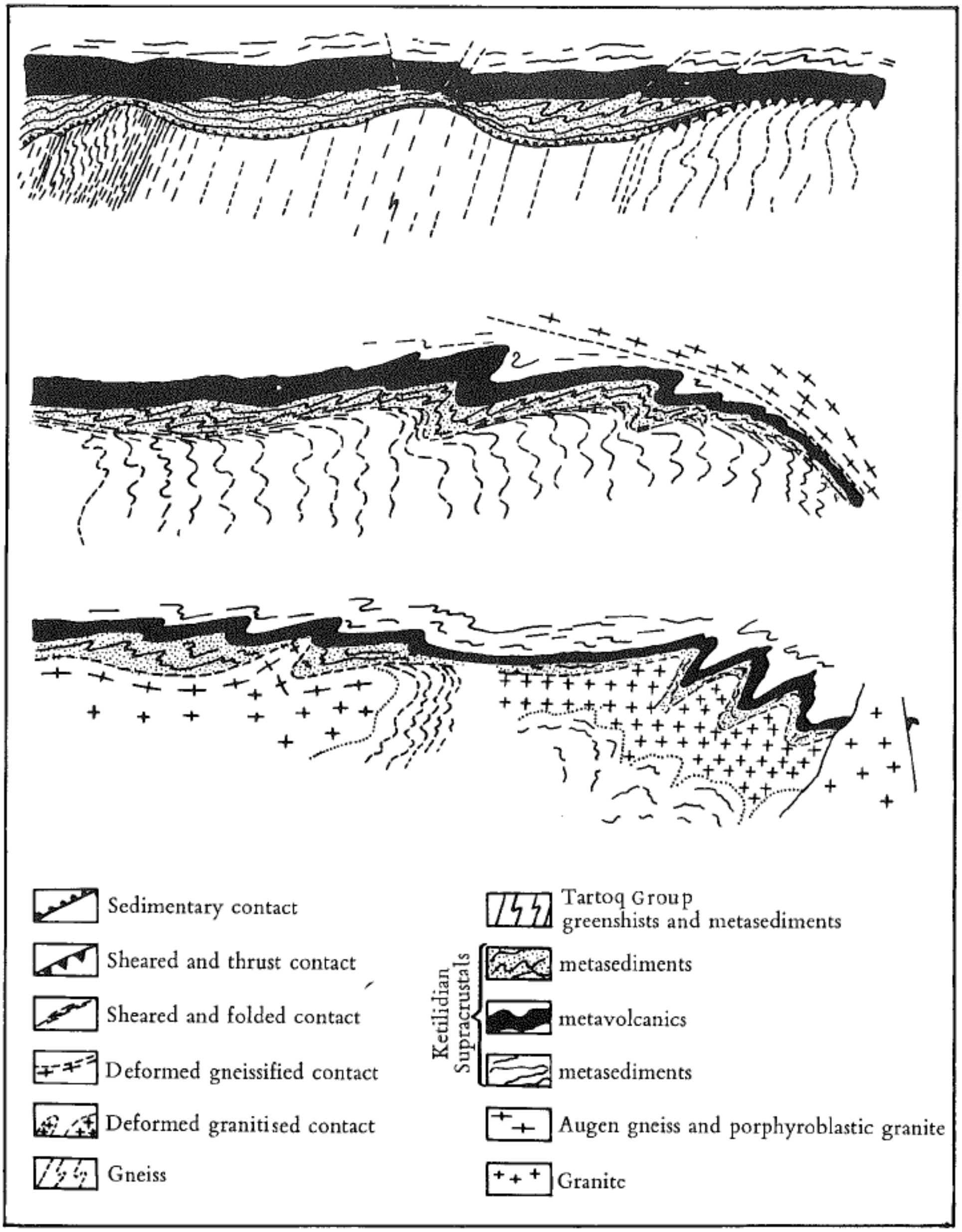


Fig. 9. Schematic longitudinal section along the contact between Ketilidian supracrustal and infracrustal rocks. Folds in the supracrustals of the Midternæs - Arsuk Fjord section represent second phase folds. Diagrams are not to scale.

transitional border zone up to 400 m wide. On Sánerut, in the southernmost part of the region, the most intense tectonic and metamorphic transformations are spatially associated with granitic rocks formed by granitisation (fig. 10e). The formation of these granites was in places structurally controlled within anticlinal cores and mobilisation locally gave rise to intrusive contacts with the supracrustal rocks.

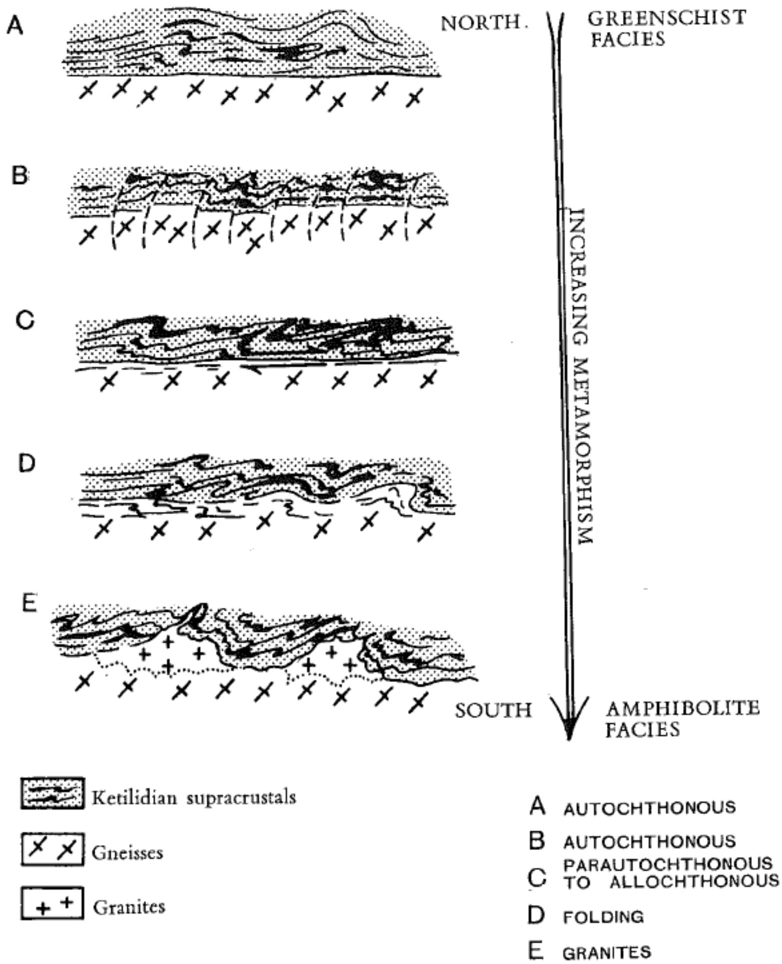


Fig. 10. Schematic representation of the development of the border relations between the Ketilidian supracrustals and their underlying infracrustals.

At Arsuk Ø there is a tectonised and conformable relationship between the two rock groups.

In association with the southward increase in deformation of the border zone, there is a concomitant increase in the grade of regional metamorphism of the Ketilidian supracrustal rocks. This takes place over a horizontal distance of about 80 km. On Midternæs and in north Grænseland there is little or no evidence of recrystallisation; slight metamorphism under low greenschist facies conditions is witnessed by the appearance of chloritic shreds amongst the primary minerals. In central Grænseland the rocks were more extensively recrystallised under greenschist facies conditions with formation of chlorite, muscovite, albite and quartz. In south Grænseland epidote-amphibolite facies conditions prevailed, biotite and epidote appearing as essential minerals. Between Arsuk Fjord and Qôrnoq staurolite and garnet occur in pelitic schists indicating high epidote-amphibolite to low amphibolite facies. Further to the south on Sánerut, in rocks of similar composition, there is found a staurolite-garnet-sillimanite-andalusite-tourmaline-biotite-plagioclase assemblage which crystallised under amphibolite facies conditions.

The general picture of southward increase in regional metamorphism of the supracrustal rocks is illustrated as follows:

Midternæs North Grænseland	Non-metamorphosed or very low greenschist facies
Central Grænseland	Greenschist facies
South Grænseland	Epidote-amphibolite facies
Arsuk Fjord-Qôrnoq	High epidote-amphibolite to low amphibolite facies
Sánerut	Amphibolite facies

It is clear that in the Ivigtut region there is a unique example of the progressive deformation of a sedimentary unconformity in association with the progressive metamorphism of the supracrustal rocks. In the southernmost part of the region the most intense tectonic and metamorphic transformations have given rise to a conformable and transitional border zone between the infracrustal and supracrustal rocks which simulates a migmatite front relation between an infrastructure and a superstructure.

IV RELEVANCE OF THE CONCLUSIONS TO THE CHRONOLOGY OF SOUTH-WEST GREENLAND

The first modern interpretation of the Precambrian geology of South Greenland was given by Wegmann (1938, 1939, 1948) who distinguished three geological cycles: pre-Ketilidian, Ketilidian and Gardar. As here we are only occupied with pre-Ketilidian and Ketilidian problems it suffices to mention that Wegmann (1938) described the Ketilidian cycle as that in which the geosynclinal deposits of Arsuk Ø, Kobberminebugt and Tasermiut were formed and subsequently folded and metamorphosed. Wegmann found evidence of pre-Ketilidian rocks only as pebbles in Ketilidian conglomerates. He later recognised that part of the gneisses of the Ivigtut region might be pre-Ketilidian, forming the basement for the Ketilidian deposits (Wegmann, 1939, 1948). Wegmann divided the Ketilidian deposits into two: the Sermilik Group, a largely sedimentary group best developed around Tasermiut, 200 km south-east of Ivigtut, and the largely volcanic Arsuk Group of Arsuk Ø and Storø. Between the two areas there are almost no traces of Ketilidian supracrustals, therefore there is no proof that the two groups of supracrustals belong to the same cycle, although it seems very probable (Wegmann, 1938, p. 55; Allaart, 1964; Bridgwater, 1965, p. 9).

Since 1954 GGU geologists have been working in south Greenland, and even if Wegmann's chronological scheme has been extended, it has not been rejected. Accounts of the more recent interpretations of the chronology are given by Allaart (1964), Berthelsen (1960, 1961, 1962), Berthelsen and Noe-Nygaard (1965), Bridgwater (1965) and Watterson (1965).

Berthelsen and Noe-Nygaard (1965) concluded that the superstructure and part of the infrastructure in the Ivigtut region are of Ketilidian age although part of the gneisses must be pre-Ketilidian. The type area chosen for the Ketilidian deposits in the Ivigtut region was Grænseland, with the Vallen and Sortis Groups, which were considered to be succeeded by the upper part of the deposits at Qipisarqo (the Qipisarqo Group). The gneisses in Grænseland were known by Berthelsen (1962) to be pre-Ketilidian but were believed to be an upthrust wedge.

Up to 1960 the geologists' field work in the Ivigtut region seemed to confirm the theory that the greater part of the gneisses had been formed from Ketilidian deposits by migmatisation. The supracrustals - all believed to be of Ketilidian age - appeared to form a cover for the underlying gneisses, and to make up a ring from the Sánerut belt in the south to Qôrnoq, Grænseland, Midternæs, along the coast of Sermiligârssuk to Tartoq; from there it was thought to continue, covered by the sea, to Arsuk Ø, Storø and back to Sánerut. As the main structures (foliation and bedding) of the infracrustals and supracrustals are conformable and as the border relations between them had been seen most clearly at Tartoq, where there is a transitional migmatite front between the two series, it was presumed that a migmatite front relation was characteristic for the Ivigtut region and both units were of Ketilidian age.

The mapping of Grænseland brought the first conclusive evidence that at least part of the gneisses in the Ivigtut region formed a basement to the Ketilidian supracrustals. This was further confirmed by more recent mapping on Midternæs, where the pre-Ketilidian basement contains both gneisses and supracrustal greenschists, both of which are cut by the Ketilidian basal unconformity. This demonstrates that the supracrustals of the Ivigtut region are partly of Ketilidian and partly of pre-Ketilidian age. The resulting modified chronological scheme is presented in the introduction. Unfortunately Berthelsen (1960) and Berthelsen and Noe-Nygaard (1965) did not have the evidence to distinguish between the pre-Ketilidian (Tartoq Group) greenschists and the Ketilidian supracrustals.

Allaart (1964) gave a review of the work done on the Ketilidian and pre-Ketilidian rocks in South Greenland. South of the Ivigtut region guaranteed pre-Ketilidian rocks have not been demonstrated and if they are present they must have been considerably reconstituted. Allaart gave several possibilities of correlation between the Ivigtut region and the areas south-east of it. For the Ivigtut region he gave two possible chronologies:

Ivigtut A: The Ivigtut gneisses are formed during a pre-Ketilidian plutonic period, and some of the metadolerites (Kuanitic dykes) are formed after that, but before the Ketilidian period.

Ivigtut B: The Ivigtut gneisses are Ketilidian in age, only the gneisses of Grænseland are pre-Ketilidian, and the metadolerites are post-Ketilidian.

On the available evidence the writers consider that Allaart's "Ivigtut A" scheme is much the more likely chronology for the Ivigtut region.

Bridgwater (1965) gave the most recent summary of the geological events in South Greenland. When discussing the major geological problems he gave the following theoretical possibilities for the supracrustal-infracrustal relations in the Ivigtut region after the discovery of the Ketilidian basal conglomerate in Grænseland (Bridgwater, 1965, pp.18-19):

"a) The gneiss below the Ketilidian basal conglomerate is a wedge of rock older than the adjacent Ivigtut gneisses. It represents the only recognisable pre-Ketilidian rocks in the area, which have been preserved by faulting (Berthelsen, 1962, plate 7).

b) The supracrustal rocks surrounding the Ivigtut gneisses belong to two different periods of sedimentation. As the base of the Ketilidian is defined at the basal conglomerate from Grænseland, then both the Ivigtut gneisses and the supracrustal rocks from which they were formed are pre-Ketilidian.

c) The infrastructure is an older pre-Ketilidian core of gneisses with a mantle of Ketilidian low metamorphic rocks comparable to the classic mantle gneiss domes described by Eskola (1949). The Grænseland unconformity is the only place where the original relationship is preserved. In other places the original unconformity has been destroyed by Ketilidian reactivation of the older gneisses."

The information presented in this report suggests that the interpretation given in b) above accords best with what is known of the Ivigtut region, with the reservation that in the southernmost part there may be some gneisses of Ketilidian age (see section V). However, although some analogy with the Eskola's mantled gneiss domes is acceptable, it is better to view the conformable border relations in the southern Ivigtut region as a tectonised and gneissified unconformity without dome-structure influence.

The essential conclusion that can be drawn from the relations of metadolerites (discordant amphibolites) described above (p.24) is that, after the emplacement of the dykes, the older country rocks were reworked and the dykes were metamorphosed and deformed. This reasoning is well known from the work of Sederholm (1923, 1926, 1934). When the greater part of the gneisses in the Ivigtut region were believed to be Ketilidian, the metadolerites were thought to be younger, intruded into tensional fractures after the consolidation of the Ketilidian rocks. This period was named the Kuanitic (from Kuánit fjord situated 18 km north-west of Ivigtut) and the subsequent period of plutonic reactivation, which transformed the "Kuanitic dykes", was named the Sanerutian (Berthelsen, 1960).

Metadolerites were described by Bondesen and Henriksen (1965) from the region near Kuánit fjord. The dykes were interpreted as Kuanitic, and it was shown that the metamorphism of the dykes increased from greenschist facies under static conditions in the west, to amphibolite facies under dynamic conditions in the east of the area studied.

Watterson (1965) made a detailed study of different types of metamorphosed basic dykes in the Ilordleq area, which is situated south-east of Sánerut. He defined three types of metadolerites (discordant amphibolites): DA_1, DA_2 and DA_3. The DA_1 s, only found as remnants within supracrustal rocks of Ketilidian age, were emplaced before or during the Ketilidian deformation period. The younger DA_2s were emplaced during anorogenic conditions into tensional fractures; this places them in the Kuanitic period as defined above. The DA_3s are the youngest dykes, emplaced along compressional shear zones during the closing stages of Sanerutian plutonism. The foliation pattern and the texture of the DA_3s are very characteristic and completely unlike those of the other DA types.

The new evidence presented by Higgins and Bondesen (1966) and further described in this paper leads to a better understanding of the relations between the pre-Ketilidian, the Ketilidian and the metadolerites ("Kuanitic dykes") in the Ivigtut region and can be summarised as follows:

1. Besides post-tectonic dykes only two small discordant amphibolitic dykes are found cutting Ketilidian rocks; they are inter-Ketilidian and probably equivalent to Watterson's DA_1 s.
2. Except for these two examples none of the many amphibolitic dykes cut the base of the Ketilidian supracrustals, nor are any seen within them.
3. Some of the metadolerites must be later than the deposition of the Tartoq Group, and the pre-Ketilidian phases of metamorphism and migmatisation which affect the Tartoq Group; these dykes are found cutting the Tartoq Group greenschists and the bordering gneisses.
4. The transformation of at least some of the dykes increases from north-west to south-east. South of Ivigtut they are only seen as folded and disrupted dykes in the gneisses (Berthelsen, 1962).
5. Where the metadolerites are dyke-like (north of Arsuk Fjord), they are mostly wide (2-50 m). The amphibolitic dykes which Watterson (1965) has described, are small, usually 1-2 m in width. Therefore it is difficult to directly compare the dykes from the two areas.
6. In other parts of South Greenland there are metadolerites of true Kuanitic age, i.e. post-Ketilidian dykes affected by Sanerutian transformations (Allaart, 1964, Watterson, 1965). Representatives of these dykes might be present in the Ivigtut region, but they have not been demonstrated.

It can be seen that what originally were termed "Kuanitic dykes" in the Ivigtut region can include discordant amphibolite dykes from several periods. Some of the dykes are Ketilidian, but the majority of the dykes were probably intruded in pre-Ketilidian time. Also the presence of post-Ketilidian amphibolite dykes, described by Watterson (1965) as DA_2 and DA_3, cannot be excluded.

At present it is impossible to tell if the metadolerites were transformed during one or both of the Ketilidian and Sanerutian plutonic periods. As yet not enough is known about the chronology of the different types and generations of metadolerites in the Ivigtut region, and therefore it is not surprising that demonstration of pre-Ketilidian country rocks was not made by means of the metadolerites.

It was thought by Berthelsen (1961, pp. 332 and 336) that the Ketilidian rocks continued farther north along the west coast of Greenland, and that the supracrustal rocks recorded from the region north of Sermiligârssuk were also of Ketilidian age. However, the discovery of the unconformity between Ketilidian supracrustals and an older group of supracrustals makes this assumption less likely. The establishment of a basement for the Ketilidian supracrustals in the form of the Tartoq Group supracrustals and gneisses partly derived from the Tartoq Group will prove of the greatest importance for the chronology of the whole of west Greenland.

V SOME SUGGESTIONS

In the following section there are given some suggestions with respect to different aspects of the geology of south-west Greenland. The evidence on which these suggestions are based is circumstantial and inadequate for positive conclusions; nevertheless, they provide useful pointers to probable relations and thus afford fruitful lines of inquiry for future research.

The relative age of the supracrustal rocks that underlie and overlie the Midternæs unconformity are satisfactorily known. However, there remains the problem of the age of the supracrustals near Ravns Storø. It is considered quite likely that they, like the Tartoq Group supracrustals, are of pre-Ketilidian age. The main reason for concluding this age relationship is the fact that the deformation and metamorphism of the Ketilidian supracrustal rocks in the Ivigtut region decreases progressively northwards. If the deformation and metamorphism of the Ravns Storø supracrustals is of Ketilidian age, then these effects must increase again northwards, a feature which is thought to be unlikely. This leaves it most probable that the deformation and recrystallisation of these supracrustals took place in pre-Ketilidian time, and therefore that they were deposited in pre-Ketilidian time.

From a survey of the literature it can be seen that there has been considerable disagreement concerning the age of the gneisses in the Ivigtut region (Wegmann, 1938; Berthelsen, 1960 and 1961; Bridgwater, 1965). It should be noted that Higgins and Bondesen (1966) regard only the gneisses in a zone immediately adjacent to the Tartoq Group supracrustals as transformed representatives of that group. Berthelsen's (1960, fig.1) structural map of the Ivigtut region reveals a stratigraphy in the gneisses folded systematically on NW- to NE-trending axes. This stratigraphy might be representative of transformed sequences of an original rock succession of which the Tartoq Group is a part, or alternatively be that of the basement on which the Tartoq Group was deposited; in the latter case any original unconformity would have been obliterated by subsequent transformations. In either event the bulk of the Ivigtut gneisses are interpreted as of pre-Ketilidian origin, but it must be stated that locally, and particularly in the southern part of the region where the effects of Ketilidian plutonism have been greatest, there may be gneisses of Ketilidian age.

With reference to map 1 it can be seen that in the Sánerut area the structural trend of the most highly deformed supracrustal rocks is NE-SW, this probably representing the regional orogenic trend of the Ketilidian. As there is a Ketilidian basal conglomerate in Grænseland, and as the Ketilidian supracrustal rocks consistently young to the south-east, it is suggested that the border zone of the Ketilidian geosyncline was situated in the Ivigtut region and that the axis of the geosyncline was further to the south-east, probably somewhere in the Julianehåb district. It should not be forgotten in this respect that there are well-preserved supracrustal rocks on and near Mato island (Nesbitt, 1961), near Julianehåb. If they were deposited during the Ketilidian period then they have survived both the Ketilidian plutonism and the Sanerutian reactivation (Allaart, in press).

Acknowledgments

The writers wish to thank the director of Grønlands Geologiske Undersøgelse, K. Ellitsgaard-Rasmussen, for permission to publish this report. We are also grateful to Messrs. J. Muller, N. Kelstrup and F. L. Jacobsen for allowing us to quote their unpublished material.

References

Allaart, J.H. (1964) Review of the work on the Precambrian (pre-Gardar) basement between Kobberminebugt and Frederiksdal, South Greenland. Rapp. Grønlands geol. Unders., Nr.1.

------- (in press) Basic and intermediate igneous activity and its relationships to the evolution of the Julianehåb granite, South Greenland. Medd. Grønland, Bd.175, Nr.1.

Ayrton, S.N. (1963) A contribution to the geological investigations in the region of Ivigtut, SW-Greenland. Medd. Grønland, Bd.167, Nr.3.

Berthelsen, A. (1960) An example of a structural approach to the migmatite problem. Rep. 21st. Intern. geol. Congr. Norden, Part 14, 149-157.

------- (1961) On the chronology of the Precambrian of western Greenland. In Raasch, G.O. (edit.) Geology of the Arctic, Vol.1, 329-338. Proc. 1st. Intern. Symp. Arctic Geology. Toronto.

------- (1962) On the geology of the country around Ivigtut, SW-Greenland. Geol. Rdsch., 52, 269-279.

-------, Bondesen, E. and Jensen, S.B. (1962) On the so-called wildmigmatites. Krystalinikum, 1, 31-50.

------- and Noe-Nygaard, A. (1965) The Precambrian of Greenland. In Rankama, K. (edit.) The Precambrian, Vol. 2, 113-262. London and New York. Interscience Publ.

Bondesen, E. (in prep.) The stratigraphy and deformation of the Precambrian rocks of the Grænseland area, South-West Greenland. Medd. Grønland.

------- and Henriksen, N. (1965) On some pre-Cambrian metadolerites from the central Ivigtut region, SW Greenland. Medd. Grønland, Bd.179, Nr.2.

Bridgwater, D. (1965) Isotopic age determinations from South Greenland and their geological setting. Medd. Grønland, Bd.179, Nr.4.

Eskola, P.E. (1949) The problem of mantled gneiss domes. Quart. J. geol. Soc. Lond., 104, 461-476.

Haller, J. (1955) Der "Zentrale Metamorphe Komplex" von NE-Grønland. I. Die geologische Karte von Suess Land, Gletscherland und Goodenoughs Land. Medd. Grønland, Bd. 73, Afd. 1, Nr. 3.

Higgins, A.K. and Bondesen, E. (1966) Supracrustals of pre-Ketilidian age (the Tartoq Group) and their relationships with Ketilidian supracrustals in the Ivigtut region, South-West Greenland. Rapp. Grønlands geol. Unders., Nr. 8.

Jacobsen, F.L. (1961) Beskrivelse af en kvartsdioritisering af amfibolitisk grønsten ved N og S Kanek, N-lige del af Ivigtutkortbladet. Unpublished thesis, Grønland geol. Unders.

Nesbitt, R.W. (1961) The petrology and structure of the country around Julianehaab, south-west Greenland. Unpublished Ph.D. thesis, Durham Univ. England.

Oftedahl, C. (1964) The nature of the basement contact. Studies in the Trondheim region. Norges geol. Unders., 227, 5-12.

Poulsen, V. (1964) The sandstones of the Precambrian Eriksfjord formation in South Greenland. Rapp. Grønlands geol. Unders., Nr. 2.

Ramsay, J.G. (1958) Moine-Lewisian relations at Glenelg, Inverness-shire. Quart. J. geol. Soc. Lond., 113, 487-523.

------- (1963) Structure and metamorphism of the Moine and Lewisian rocks of the north-west Caledonides. In Johnson, M.R.W. and Stewart, F.H. (edit.) The British Caledonides. London: Oliver and Boyd, 143-175.

Sederholm, J.J. (1923) On migmatites and associated Precambrian rocks of SW Finland. Pt. I. The Pellinge area. Bull. Comm. géol. Finl., 58.

------- (1926) idem. Pt. II. The region around Barosundsfjord W of Helsingfors and neighbouring areas. Bull. Comm. géol. Finl., 77.

------- (1934) idem. Pt. III. The Åland islands. Bull. Comm. géol. Finl., 107.

Shackleton, R.M. (1953) The structural evolution of North Wales. Lpool Manchr geol. J., 1. pt. 3, 261-297.

Watterson, J.S. (1965) Plutonic development of the Ilordleq area, South Greenland. Part. I. Chronology, and the occurrence and recognition of metamorphosed basic dykes. Medd. Grønland, Bd. 172, Nr. 7.

Wegmann, C.E. (1935) Zur Deutung der Migmatit, Geol. Rdsch., 36, 305-350.

------- (1938) Geological investigations in southern Greenland. I. On the structural divisions of southern Greenland. Medd. Grønland, Bd.113, Nr.2.

------- (1939) Übersicht über die Geologie Südgrönlands. Mitt. naturf. Ges. Schaffhausen, Bd.16, Jahrgang 1940, 188-212.

------- (1948) Note sur la chronologie des formations précambriennes du Groenland méridional. Ecl. geol. Helv., 40, 7-14.

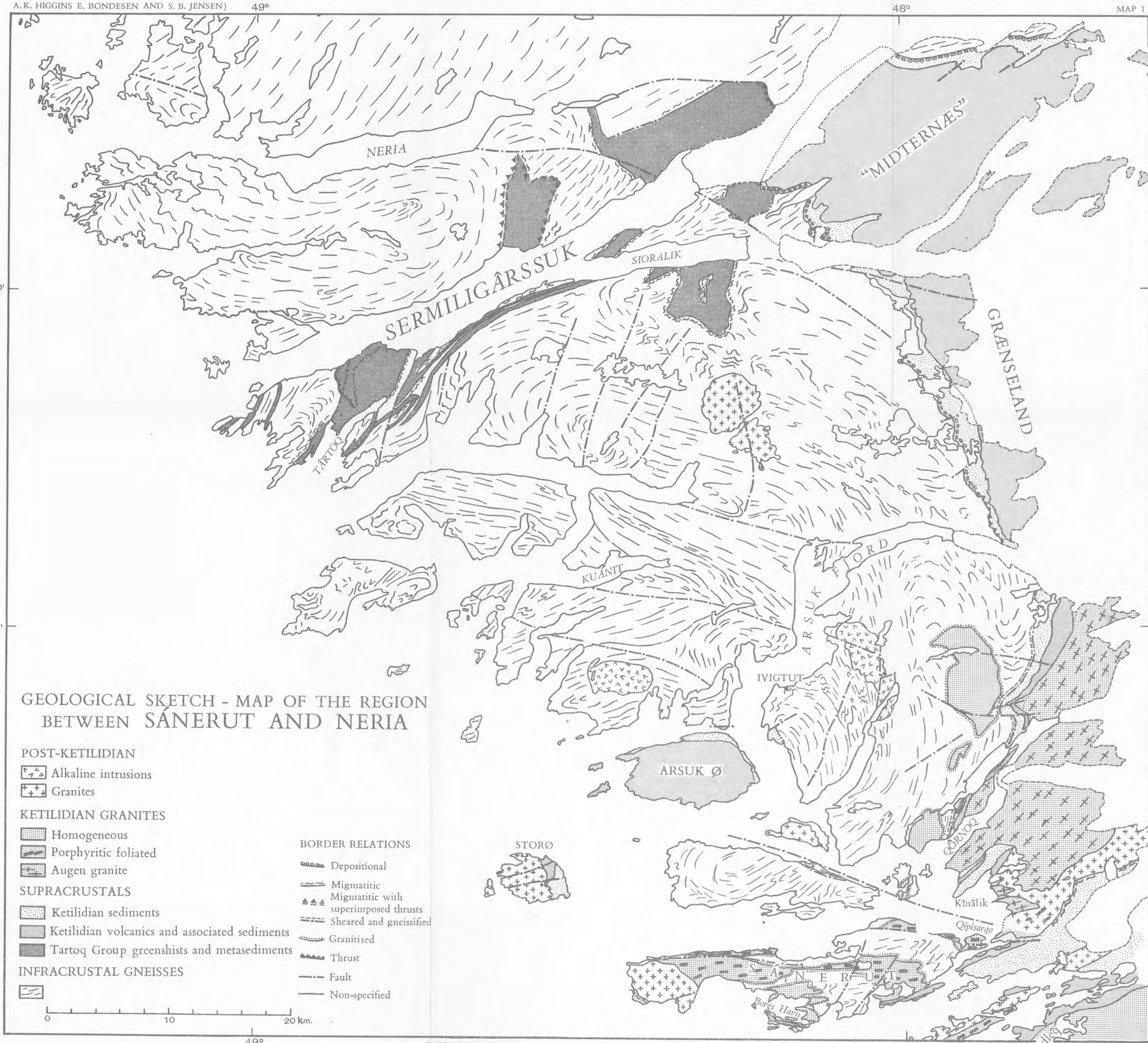
------- and Kranck, E.H. (1931) Beitrage zur Kenntnis der Svecofenniden in Finlande. I. Übersicht über die Geologie des Felgrundes im Kustengebiete zwischen Helsingfors und Onas. II. Petrologische Übersicht des Gebietes E von Helsingfors. Bull. Comm. géol. Finl., 89, 1-107.

Weidmann, M. (1964) Géologie de la region située entre Tigssaluk fjord et Sermiligârssuk fjord (partie médiane), SW-Groenland. Medd. Grønland, Bd.169, Nr.5.

Zwart, H.J. (1963) The structural evolution of the Palaeozoic of the Pyrenees. Geol. Rdsch., 53, 170-205.

GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

G G U RAPPORT NR. 9 (B. F. WINDLEY N. HENRIKSEN A. K. HIGGINS E. BONDESEN AND S. B. JENSEN)



BASED ON MAPPING BY: S. AYRTON, A. BERTHELSEN, E. BONDESEN, L. BONNARD, M. BURRI, C. H. EMELEUS, C. FROIDEVAUX, N. HENRIKSEN, A. K. HIGGINS, F. L. JACOBSEN, S. B. JENSEN, F. KALSBEEK, N. KELSTRUP, J. MÜLLER, B. UPTON, C. PULVERTAFT, S. WATT AND M. WEIDMANN.

Grønlands Geologiske Undersøgelse
Recent publications

Bulletins

reprinted from Meddelelser om Grønland

No. 58 The composite net-veined diorite intrusives of the Julianehåb district, South Greenland. 1965 by B. F. Windley.

No. 59 The deformation and granitisation of Ketilidian rocks in the Nanortalik area, S. Greenland. 1966 by A. Escher.

No. 60 The layered aplite-pegmatite sheets of Kînâlik, South Greenland. 1965 by B. Windley and D. Bridgwater.

No. 61 Sorensenite, a new sodium-beryllium-tin-silicate from the Ilímaussaq intrusion, South Greenland. 1965 by E. I. Semenov, V. I. Gerassimovsky, N. V. Maksimova, S. Andersen and O. V. Petersen.

No. 62 Geomorphological observations on Sermersôq; a contribution to the geomorphology of S. Greenland. 1965 by Oen Ing Soen.

No. 63 Eudidymite and epididymite from the Ilímaussaq alkaline intrusion, South Greenland. 1966 by E. I. Semenov and H. Sørensen.

Miscellaneous Papers

reprinted from various journals

No. 47 Genesis of rapakivi. 1966 by P. R. Dawes.

No. 48 Observations on recent sand volcanoes. 1966 by E. Bondesen.

Reports

No. 1 Review of the work on the Precambrian basement (pre-Gardar) between Kobberminebugt and Frederiksdal, South Greenland. 1964 by J. H. Allaart. D.kr. 7.00

No. 2 The sandstones of the Precambrian Eriksfjord formation in South Greenland. 1964 by V. Poulsen. D.kr. 2.50

No. 3 The bedrock geology of Vatnahverfi, Julianehåb district, South Greenland. 1966 by J. P. Berrangé. D.kr. 7.50

No. 4 Jordtemperaturmålinger i Frederikshåb. 1965 by O. Olesen. D.kr. 1.50

No. 5 The Precambrian geology of the Sârdloq area, South Greenland. 1966 by B. F. Windley. D.kr. 7.00.

No. 6 Chemical analyses from the Gardar igneous province, South Greenland. 1966 by W. S. Watt. D.kr. 7.50.

No. 7 On the magmatic evolution of the alkaline igneous province of South Greenland. 1966 by H. Sørensen. D.kr. 2.50.

No. 8 Supracrustals of pre-Ketilidian age (the Tartoq Group) and their relationships with Ketilidian supracrustals in the Ivigtut region, South-West Greenland. 1966 by A. K. Higgins and E. Bondesen. D.kr. 2.50

Bulletins and Miscellaneous Papers are only available on exchange with institutions and libraries. Reports are obtainable on exchange, or may be purchased from Grønlands Geologiske Undersøgelse, Østervoldgade 5-7, Copenhagen K, Denmark.