GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT NR. 27

The Geological Survey of Greenland
Report no. 27

Some observations on the structural and metamorphic chronology on Agto and surrounding islands, central West Greenland

by

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KØBENHAVN 1970

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Østervoldgade 10, DK-1350 Copenhagen K

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SOME OBSERVATIONS ON THE STRUCTURAL AND METAMORPHIC CHRONOLOGY ON AGTO AND SURROUNDING ISLANDS, CENTRAL WEST GREENLAND

by

Kai Sørensen

With 10 figures and 1 table

1970

Abstract

The report concerns an area situated in granulite facies terrain in the Precambrian Nagssugtoqidian orogenic belt (K/Ar age ca. 1700 m.y.) of central and northern West Greenland.

The acid rocks are biotite gneisses, biotite-hypersthene gneisses, granitic gneisses, granites and sillimanite- and garnet-bearing gneisses. The basic rocks are amphibolites, pyroxene amphibolites and their garnet-bearing equivalents. The basic rocks can be divided into an old, concordant group and a younger, discordant group.

In the area mapped four structural complexes characterised by different orientations of axial planes related to deformations of different times have been mapped. The youngest structures have ENE-striking axial planes - the typical Nagssugtoqidian trend.

The discordant metabasites are younger than at least two phases of folding and are preserved in the structural complex characterised by the oldest structures. They cut migmatitic structures and thus they are younger than at least one period of high grade metamorphism. The discordant metabasites are older than the youngest deformation, that which resulted in folds with ENE-striking axial planes, i.e. they are older than the typical Nagssugtoqidian structures. They are older than one period of high grade metamorphism which converted the basic dykes into pyroxene amphibolites. This period of metamorphism is at least partially contemporaneous with the Nagssugtoqidian deformation. The field occurrence of the discordant metabasites shows that they intruded into rocks affected by tensional stresses and the author proposes that the intrusion of the basic dykes marks the interval between two orogenic episodes, one Nagssugtoqidian and the other pre-Nagssugtoqidian. If this assumption is correct, all the rocks of the area are pre-Nagssugtoqidian.

The minimum temperature during the peak of metamorphism is evaluated using evidence of anatexis and the minimum pressure from the absence of cordierite.

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INTRODUCTION

The author has taken part in the mapping project in the Agto-Nagssugtôq (Nordre Strømfjord) region led by E. Bondesen (see fig. 1). The mapping started in 1966 and continued during the summers 1967 and 1968, with financial support from the Carlsberg Foundation, the Geological Survey of Greenland and the research foundation of the University of Aarhus. The progress of the work has been summarised by Bondesen (1966, 1968, 1969). The final result of this mapping project will be a 1 : 100 000 sheet of the area framed in fig. 1. During parts of the summers 1967 and 1968 the author carried out mapping on the islands Agto, Simiugaq, Ikerasarssup nunâ, Ausiait and Avdlungersat, as far as latitude 68 N. The purpose of this paper is to present some conclusions on the structural and metamorphic chronology based on the field work on these islands. In addition the new results are set in the context of the previous work.

The area is situated in the northern boundary zone of the Isortoq Complex, which constitutes the central part of the Nagssugtoqidian orogenic belt (Ramberg, 1949). The Isortoq Complex is characterised by granulite facies metamorphism. To the north in the Egedesminde Complex and to the south in the Ikertoq Complex the rocks are metamorphosed under amphibolite facies conditions.

Since Ramberg defined the Nagssugtoqides as an orogenic belt younger than the gneisses south of Søndre Strømfjord, new regional mapping and radiometric age determinations have indicated that this orogenic belt extends all the way from Søndre Strømfjord at least as far north as Upernavik (Pulvertaft, 1968). With one exception, all K/Ar age determinations within this belt fall between 1800 and 1650 m.y. but it is likely that reworked rocks of much greater age occur over much of the Nagssugtoqides (Pulvertaft, 1968), a likelihood strengthened by the results presented in this report. The part of the Nagssugtoqidian orogenic belt lying south of Disko Bugt has however a unity of its own of a primarily structural character: ENE- to NE-trending structures dominate (Ramberg, 1949). Only in a small part of the area mapped by the author do structures occur with this trend, on the following pages termed the "typical" Nagssugtoqidian trend. In the

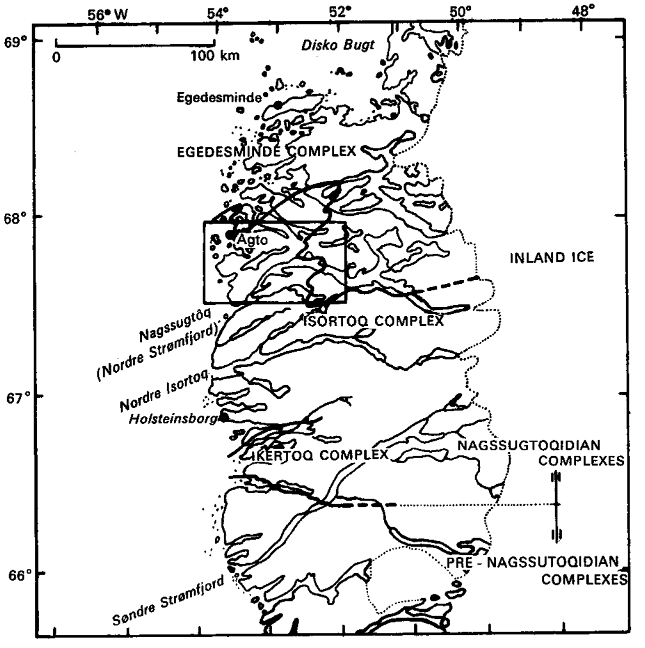

Fig. 1. The metamorphic complexes of the southern part of the Nagssugtoqidian orogenic belt, West Greenland. The Agto-Nagssugtôq region shown in frame. (After Noe-Nygaard and Ramberg, 1961).

rest of the area structures whose formation predates the formation of the typical Nagssugtoqidian structures are found. Before these structures are described a short description of the rocks of the area will be given.

THE ROCKS

The description of the rocks is based on field observations and a routine examination of approximately 150 thin sections. The place-names used and the rock groups described are found on the lithological map, fig. 2.

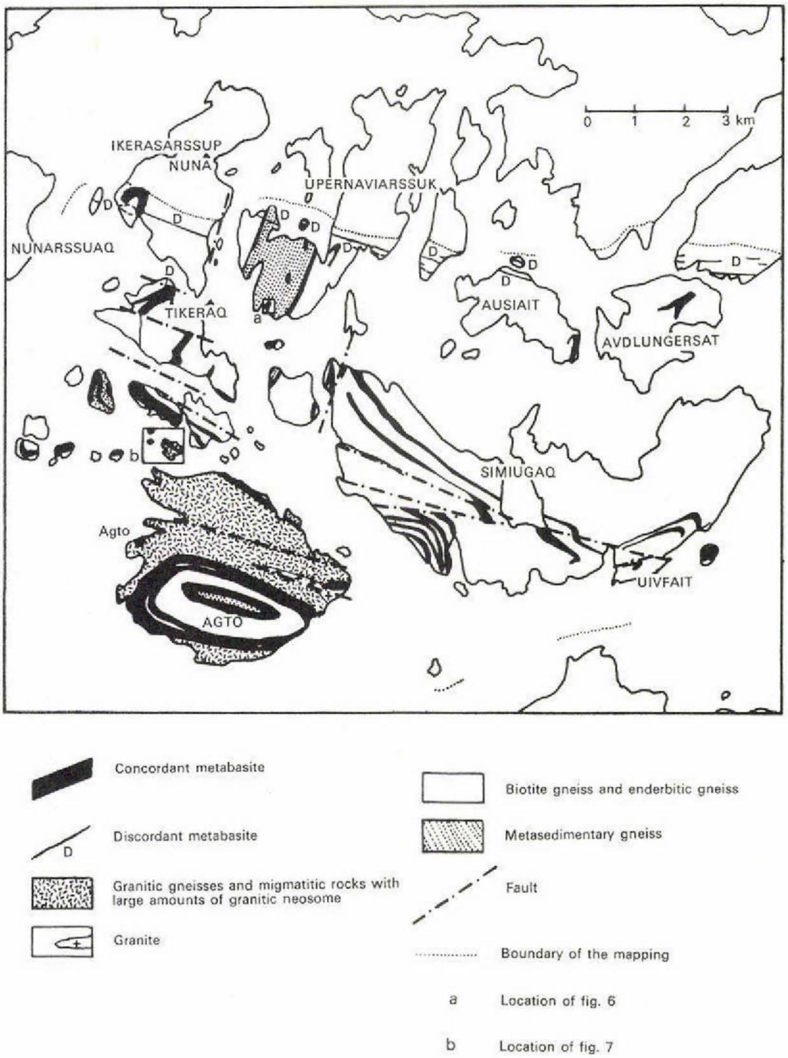

Fig. 2. Simplified lithologic map of the Agto area.

Basic rocks

The basic rocks of the area are amphibolites, pyroxene amphibolites, pyribolites (Berthelsen, 1960, pp. 20-21), and their garnet-bearing equivalents. According to age the metabasic rocks can be referred to two groups: concordant (older) and discordant (younger) metabasites.

Concordant metabasites

The minerals found are plagioclase, hornblende, orthopyroxene, clinopyroxene, garnet, biotite and quartz. The five minerals mentioned first are combined in 8 parageneses which may or may not contain minor amounts of biotite and quartz. All parageneses contain hornblende. The parageneses which contain orthopyroxene are therefore grouped in the hornblende-granulite sub-facies of the granulite facies (Fyfe, Turner and Verhoogen, 1958).

The parageneses which do not contain orthopyroxene are:
hornblende + plagioclase
hornblende + plagioclase + clinopyroxene
hornblende + plagioclase + garnet
hornblende + plagioclase + clinopyroxene + garnet.

The classification of this last mentioned paragenesis in the sub-facies system of de Waard is uncertain. As for acid rocks the co-existence garnet-clinopyroxene is characteristic of the hornblende-clinopyroxene-garnet sub-facies of de Waard (1965) but in the case of basic rocks the physical conditions of the formation of this paragenesis are at least partially dependent on the chemistry of the rocks, notably the ratio Fe/Mg, as shown by experiments (Green and Ringwood, 1966) and petrologic work (e.g. Binns, 1965).

The orthopyroxene-bearing parageneses are:
hornblende + plagioclase + orthopyroxene
hornblende + plagioclase + orthopyroxene + clinopyroxene
hornblende + plagioclase + orthopyroxene + garnet
hornblende + plagioclase + orthopyroxene + clinopyroxene + garnet.

Parageneses with or without orthopyroxene show no systematic distribution within the limited area studied. Obviously investigations of quantitative and qualitative mineralogic variations related to changes in metamorphic grade must include larger areas.

The concordant metabasites are found with highly varying structures, e.g. streaky, banded, agmatitic and other migmatitic structures. Examples of banded and agmatitic structures are sketched in fig. 3. More profound studies of the origin of these structures must necessarily be based on detailed mapping and laboratory investigations. It is later pointed out that at least some of these structures have been formed early in the history of the area.

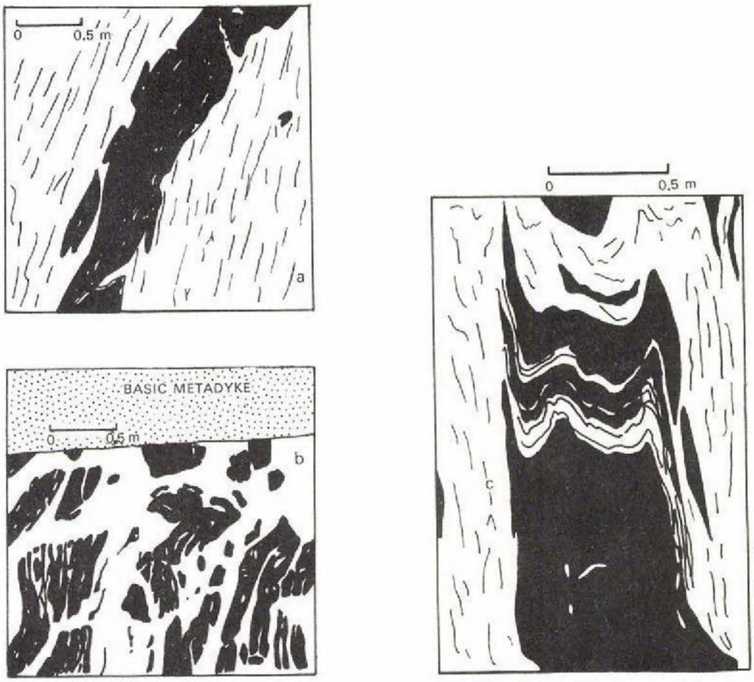

Fig. 3. Migmatitic structures in metabasites.

a: Migmatitic metabasite, Simiugaq. Drawn from photograph by E. Bondesen.

b: Agmatitic metabasite, cut by a basic metadyke. Upernaviarssuk.

c: Banding in a minor body of metabasite. Also shown to illustrate the heterogeneity of the F_4 deformation. Umanaussaq.

Discordant metabasites

The discordant metabasites do not differ in mineral content from the concordant ones. However, the former have higher ratios of pyroxene to amphibole, a feature which may be easily explained by their pre-metamorphic mineralogy, which was poor in or showed a total lack of hydroxyl-bearing minerals.

In contrast to the concordant metabasites the discordant metabasites are homogeneous, fine- to medium-grained and granular. Relics of ophitic texture have not been observed. In a few localities granulated and recrystallised plagioclase phenocrysts are seen. Apophyses and other features characteristic of basic dykes are common. The relations of the discordant metabasites to the surrounding rocks and their distribution will be considered later in this paper, when their chronological significance is discussed.

Biotite gneisses and enderbitic gneisses

The largest part of the rocks in the area consists of biotite gneisses and biotite-orthopyroxene gneisses of quartz dioritic to granodioritic composition. Orthopyroxene-bearing gneisses of this composition may be termed enderbitic (Tilley, 1936). The minerals found in these rocks are quartz, plagioclase (often antiperthitic), microcline (microperthitic), biotite, hornblende, orthopyroxene, clinopyroxene and garnet.

Parageneses with and without orthopyroxene are intermingled at all scales. A low content of microcline is characteristic of this group of rocks. This fact is in harmony with the average chemical composition of the gneisses of the Isortoq Complex calculated by Ramberg (1951). Ramberg showed that a low content of K_2O distinguished the Isortoq Complex gneisses from the Egedesminde Complex gneisses, and he concluded that the chemical difference between these two groups of rocks reflected a wholesale expulsion of notably K_2O from the granulite facies complex during metamorphism. The author cannot agree with this conclusion. In the Agto area rocks with a high content of microcline occur within rocks with a low content of microcline and vice versa, as shown in table 1. In a later section evidence is put forward which suggests that these rocks suffered in common an intense deformation and high grade metamorphism during two periods of orogeny. Yet a pronounced variation in microcline content exists within this area, and no sign of large scale migration of K_2O is found; thin layers of metabasic rocks run unaffected through areas of migmatitic and non-migmatitic rocks.

A chemical difference between the gneisses of the Egedesminde and and Isortoq Complexes may instead reflect a more extensive incorporation of younger rocks in Egedesminde Complex than in the Isortoq Complex. This

Table 1

Modal composition of some acid rocks. Major minerals in vol. pct.

GGU no.	79007	79019	79001	79006	79039	79061	79066	79083
Quartz	26	32	43	32	35	25	16	35
Microcline		2	1	43	51	46	6	
Plagioclase	68	57	48	23	7	23	60	50
Biotite	1	6	5	2		6	7	3
Hornblende		1	3		3		10	12
Orthopyroxene	5	2						
Garnet					4			
Accessories							1	
Counts	500	500	500	300	500	500	500	600

79007: enderbitic gneiss, Simiugaq
79109: " " "
79001: biotite gneiss, Simiugaq
79006: neosome vein from migmatitic biotite gneiss, Simiugaq
79039: hornblende-garnet-bearing granitic gneiss, Agto
79061: nebulitic migmatite, Agto
79066: hornblende-biotite gneiss, Agto
79083: hornblende-biotite gneiss, Agto.

view is not incompatible with the fact that the boundary between the two complexes crosses the structures in the central part of Nagssugtôq, as these are the structures with the typical Nagssugtoqidian trend. Later it is shown that these structures are the last in a long sequence of deformations affecting these rocks. Thus the structural continuity is not necessarily parallel to the lithologic boundary. This will be evident from the structural description.

Metasedimentary rocks

Under this heading rocks undoubtedly or most likely of sedimentary origin are described. When the author makes use of the word "metasedimentary" instead of "supracrustal" even when some of these rocks are practically unmigmatised, it is to avoid answering the question which necessarily arises when using the latter term, viz. what is "infra" as distinct from "supra" and why?

Three groups of metasedimentary rocks occur within the area. "Group" is here used for a recognisable assemblage of rocks which is distinct in the structure of the area. The groups are:

1: The Umanaussaq group, found on the small islands Kumagtut and Umanaussaq north and north-west of Agto and on the north coast of Agto. The rocks are garnet gneisses (granulites s. str. in the sense of Noe-Nygaard and Ramberg, 1961), garnet-biotite gneisses, garnet-sillimanite gneisses, sillimanite gneisses and sillimanite-biotite gneisses. The variation in lithology often takes place within distances of a few centimetres. This may reflect an original lithologic variation, but as the history of these rocks can be shown to have been of considerable length and to include several phases of deformation, analogies with sedimentary structures may be erroneous. The metasedimentary rocks are complexly folded with garnet-bearing pyroxene amphibolites. An example of these structures is shown in fig. 7.

2: The Agto basin group which consists of granulites s. str. and garnet-biotite gneisses. These are interlayered with pyroxene amphibolites and form the core of a basin structure on the southern part of Agto, referred to as the Agto basin. The lithologic variation from acid to basic rocks is on the scale of a few metres.

3: The Upernaviarssuk group. These rocks are highly migmatitic (with granitic neosome) garnet-biotite gneisses and granulites s. str. Like the previously mentioned groups these rocks form a very distinct group which can be traced from the island Upernaviarssuk to the south and then east to the western part of Simiugaq. In this group a few layers of garnet-bearing pyroxene amphibolite interfolded with the acid rocks are found (fig. 6).

In the metasedimentary rocks quartzo-feldspathic rocks with pyrite are common. These rocks have a rusty weathering and are most common in the metasedimentary rocks, but occur also in gneisses and metabasites.

The boundaries between the metasedimentary rocks and the surrounding rocks of unknown origin are always concordant.

Migmatitic rocks

All rocks mentioned under the previous headings can be migmatitic. Migmatitic structures developed in metabasic rocks have been mentioned. Migmatisation apparently has taken place where the chemical conditions allowed the formation of a granitic neosome. In the metabasites, biotite gneisses and enderbitic gneisses the formation of a granitic neosome is never extensive. Only on Agto island do migmatites with granitic neosome constitute a large part of the rocks. Here granite and granitic gneisses also occur.

Migmatitic rocks with granitic neosome on Agto

Around the Agto basin is found a series of migmatitic rocks, granitic gneisses and a minor granite intrusion (fig. 4).

The granitic gneisses contain garnet, hornblende and biotite. They are coarse-grained, foliated and poor in migmatitic structures. Their mafic minerals are concentrated in clusters defining the foliation. These rocks can be called migmatitic because their hornblende-garnet clusters can be thought of as the melanosome part of a migmatitic rock (Mehnert, 1968). They may also be called foliated granites or autochthonous granites (Read, 1957) or orthogneisses. These terms are mentioned to indicate the direction of one's speculations on the origin of these rocks.

The garnet-bearing migmatites in the northern part of Agto are mostly developed with large, composite microcline-plagioclase-quartz "augen". Biotite and hornblende are both common constituents. In the central part of Agto, biotite-bearing, mostly nebulitic migmatites are found.

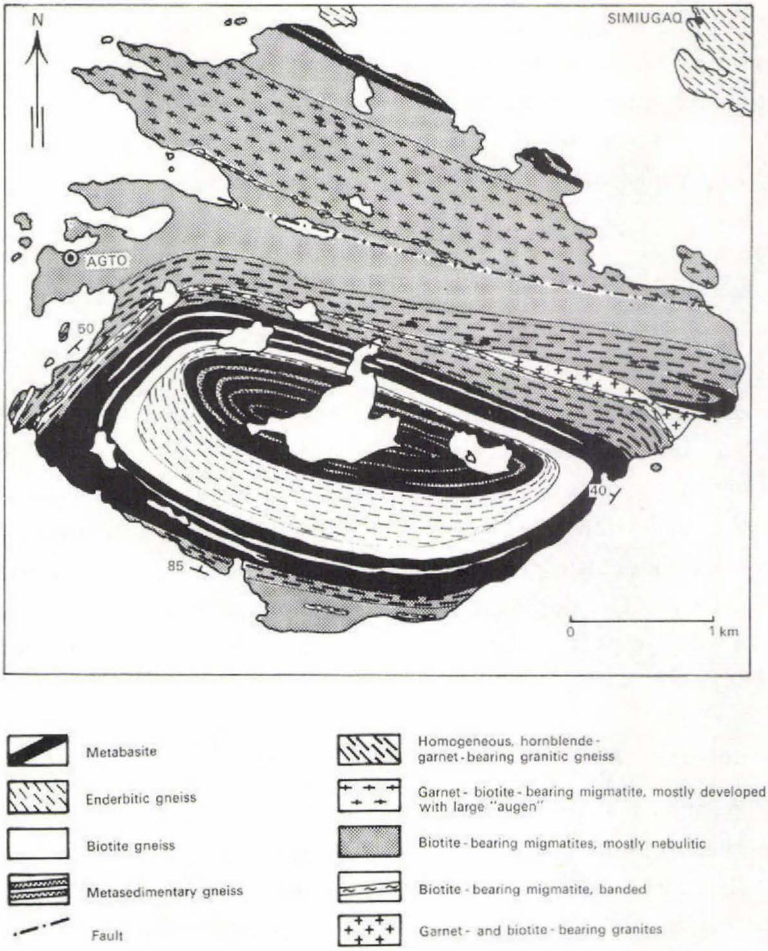

Fig. 4. Lithologic map of Agto.

Palaeosome rocks in the migmatites on Agto are the rock-types mentioned in the previous sections. On the skerries and islands west and south-west of Agto migmatitic rocks similar to those found on Agto occur. The extensive development of migmatitic rocks with granitic neosome on and around Agto is unique for the areas which so far have been mapped in the Agto-Nagssugtôq region.

In the eastern part of Agto, within the garnet-bearing granitic gneisses, a minor intrusion of coarse-grained, garnet- and biotite-bearing granite is found. It is sub-concordant with the surrounding gneisses but without foliation itself, and it can be termed a parautochthonous granite (Read, 1957).

Migmatitic rocks with granitic neosome outside Agto

Neosome of granitic composition plays only a minor role in the metabasites and gneisses outside Agto, except in the metasedimentary Upernaviarssuk group. The mineralogy of the most common gneisses (i.e. the low content of microcline) probably combined with a low water-pressure resulted in only minor amounts of granitic material being formed. The widespread but quantitatively unimportant development of granitic neosome shows that the physical conditions acting during metamorphism were suitable for migmatisation.

Migmatitic rocks with non-granitic neosome

In the metabasic rocks neosome concentrations of quartz dioritic composition are often found. This neosome may be gneissified, a fact which is in harmony with the long deformational history which these rocks have undergone (see description of the Tikeraq structural complex). In the neosome orthopyroxene may be found, and when that is the case it occurs also in the palaeosome. In the biotite gneisses and enderbitic gneisses quartz dioritic neosome segregations similar to those found in the metabasites are found.

THE STRUCTURES

Four structural complexes, i.e. areas of structural homogenity, can be outlined within the mapped area (fig. 5):

1 : The Tikeraq structural complex, which is characterised by folds with NNE-striking axial planes dipping westward.
2 : The Agto structural complex, where folds with ESE-striking axial planes which dip towards the south or have a vertical dip dominate.
3 : The Uivfait structural complex, dominated by folds with ENE- to NE-striking axial planes which dip northwards. The fourth complex, the Nunarssuaq complex (mapped by N. Roholt) is structurally similar to the Uivfait complex and will be described together with this.

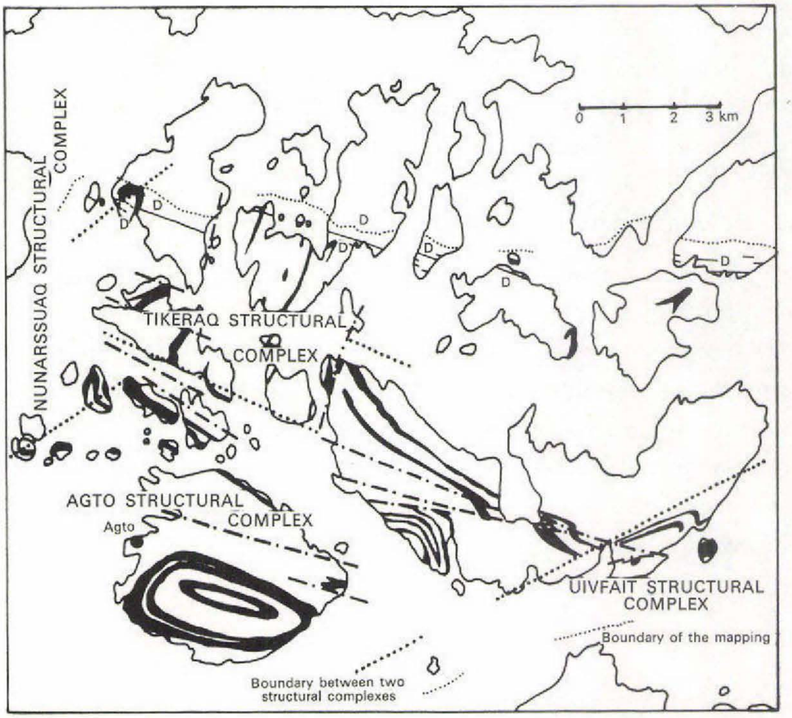

Fig. 5. The structural complexes. In black are shown the major concordant metabasites. For further explanation see the text.

The characters of the structural complexes will be briefly described and their time-space relationships will be discussed on the basis of the interference between folds resulting from deformations of different character and orientation. In the next section the relations between the phases of deformation and the intrusion of basic dykes are discussed.

The Tikeraq structural complex

The Tikeraq structural complex represents a "structural window" in the area. The dominantly NNE-striking planar structures which dip to the west result from deformation older than the deformations producing the structures characteristic of the Agto and the Uivfait structural complexes.

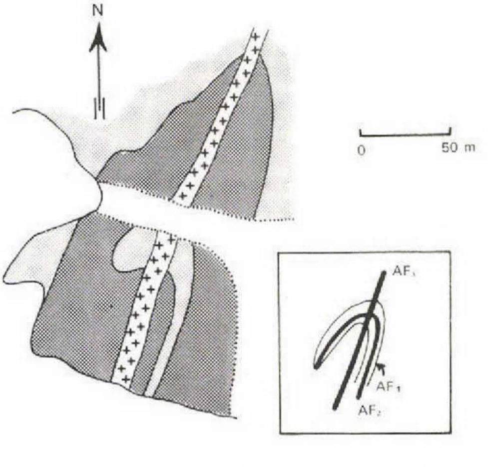

Fig. 6. Fold-interference between folds F_2 and F_3 in garnet-biotite gneiss of the Upernaviarssuk group (light grey) and garnet-bearing pyroxene amphibolite (darker grey). A pegmatitic sheet is shown with crosses. The existence of a phase F_1 is inferred from the foliation and banding.
In the inset the interference pattern is illustrated by the traces of the axial planes (A_{F3} and A_{F2}) and the strike of the foliation and banding (A_{F1}). South coast of Upernaviarssuk (for locality see fig. 2).

These younger deformations have only caused a very open folding of the NNE-striking planar structures of the Tikeraq structural complex. The folds with NNE-striking axial planes are seen to refold folds affecting the foliation of the gneisses and the banding of the concordant metabasites. This foliation and banding is thought to reflect the existence of the earliest folding and deformation, F_1. If this is the case, the folds affecting the foliation and banding may be called F_2 and the folds with NNE-striking axial planes F_3. Fold interference patterns showing the relations of F_2 and F_3 are frequent in the Tikeraq structural complex. An example is shown in fig. 6.

Metadykes of basic composition are seen to cut the structures of the Tikeraq structural complex, both the folds F_2 and F_3 and the migmatitic structures associated with these folds (fig. 3b). The chronological significance of these metadykes is discussed later.

The Agto structural complex

Along a line running parallel to the south coast of Tikeraq, the Tikeraq structures are folded by ESE-trending structures (F_4) into a ESE direction. The F_4 deformation produced folds of similar type and varying tightness. An example is shown in fig. 3c. In acid gneisses with tight folds an axial plane foliation is determined by the parallel arrangement of biotite. Sometimes hornblende marks the axial plane foliation. The formation of an axial plane foliation seems to be non-penetrative in many cases, but presumably depends on the intensity of folding (as far as this can be evaluated from the geometry of the folds) and the lithology.

Interference patterns resulting from superposition of folds F_4 upon earlier folds are widespread, the most spectacular being the Agto basin. As F_4 refolds folds with varying axial planes (folds F_2 folded by F_3) interference patterns of various types have been produced. One type is illustrated in fig. 7.

The Agto basin results from the interference of a major F_4 ESE-trending synform with a major NNE-trending F_3 synform. The basin is

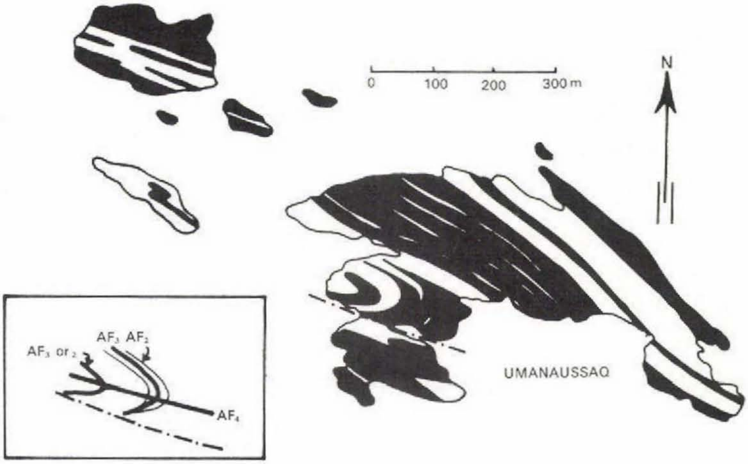

Fig. 7. Fold-interference in garnet-bearing pyroxene amphibolite (shown in black) and metasedimentary gneisses of the Umanaussaq group. The structural chronology revealed by the interference pattern on Umanaussaq just north of the fault is shown in the inset using the traces of axial planes. For locality see fig. 2.

slightly asymmetrical (fig. 4) and the almost rectangular form of the west end of the basin suggests that the F_4 movement direction may have been subparallel to the west limb of the F_3 synform and at a high angle to the planar structures of the Tikeraq structural complex. The fact that these planar structures are only little folded during the F_4 deformation shows that the boundary between the Tikeraq and Agto structural complexes marks a boundary between areas with different rate of strain during the F_4 deformation.

The Agto basin shows evidence of more than the two phases of deformation necessary to produce a structural basin. In the metabasic rocks thin layers of biotite gneiss occur (fig. 4). Where these gneiss layers disappear it can be seen that they are folds of age F_2, not F_1, as they are folds of the foliation and banding.

The part of the Agto complex lying north of the Agto basin and south of the Tikeraq structural complex constitutes the northern limb of a major F_4 synformal structure, whose axial trace divides the Agto basin parallel to its longest dimension.

The Uivfait and Nunarssuaq structural complexes

To the south-east and to the west the ESE-trending structures of the Agto structural complex are cut by ENE- to NE-trending structures, i.e. structures with ENE-striking axial planes dipping to NE. This is the typical Nagssugtoqidian trend (Ramberg, 1949). On the eastern part of Simiugaq the boundary between the Agto and Uivfait structural complexes is seen in acid gneisses. It is marked by a 90^{o} turn in the biotite foliation along a ENE-striking line. This turn takes place within a distance of a few tens of metres. The folds of this deformational phase are termed F_5. In acid gneisses an axial plane foliation is developed, mostly marked by biotite and often by hornblende. Folds of this age have not been seen in the Agto structural complex. In the Uivfait structural complex interference patterns produced by the superposition of F_5 folds on earlier structures are often found. They are of varying types.

In the west and north-west of the area structures comparable with the structures of the Uivfait structural complex are found. On Nunarssuaq they are very well developed. The boundary between the Tikeraq and the Nunarssuaq structural complexes is seen on the west coast of Ikerasarssup nunâ, but has not been mapped further to the north-east.

Faults and zones of shearing

Major faults and shear-zones postdating the formation of folds and the peak of metamorphism occur in all complexes, mostly parallel to the trend of the pre-existing structures. In these zones retrograde metamorphism has taken place and in a few places ultra-mylonitic rocks have been produced, in the field very similar to the pseudotachylites described by Jensen (1968) but never developed with glass. On account of their orientation it may be stated that they mark the end of a sequence of deformations of which they probably constitute mechanically an integral part.

BASIC METADYKES AND THEIR CHRONOLOGICAL SIGNIFICANCE

Discordant basic metadykes are found almost exclusively in the Tikeraq structural complex. In the Agto structural complex their existence is not established with certainty. In the Uivfait structural complex a few have been found. Metadykes outside the Tikeraq structural complex are deformed. Within the Tikeraq structural complex all metadykes but one, which has a northerly strike, are striking east-west.

E-W striking metadykes

A few metadykes can be traced from the west coast of Ikerasarssup nuna to the east coast of Avdlungersat. They vary in width from 0.1 to 25 metres. Even the thinnest of the metadykes can be followed as far as the exposure permits. The metadykes cut almost perpendicularly through the NNE-trending structures of the Tikeraq structural complex. On the western coast of Ikerasarssup nunâ one of these metadykes can be followed across the boundary between the Tikeraq and Nunarssuaq structural complexes. It is folded and disrupted by the F_5 deformation characteristic of the Nunarssuaq structural complex.

The N-S striking metadyke on Tikeraq

On Tikeraq island a metadyke with a N-S strike occurs. It is clearly discordant to the trend of the structures across the island. On the north coast of the island the metadyke discordantly cuts the foliation of the gneisses, but near the south coast the gneiss foliation a few metres from the dyke contact turns to become concordant with the metadyke. Apart from this concordancy the Tikeraq metadyke is in all respects similar to the E-W trending metadykes.

Metadykes outside the Tikeraq structural complex

Metadykes are extremely rare outside the Tikeraq structural complex. It was earlier mentioned that a metadyke can be followed from the Tikeraq structural complex into the Nunarssuaq structural complex where it is folded.

In the Uivfait structural complex also the discordant metadykes are deformed into folds with ENE- to NE-striking axial planes.

In the Agto structural complex no discordances have been seen between basic bodies and the surrounding rocks, but in fig. 3a is shown a thin agmatised metabasite, which might have been discordant prior to the F_4 deformation.

The age and environment of intrusion

The intrusion of the E-W striking metadykes postdates the F_3 deformation and predates the F_5 deformation.

The intrusion of the N-S striking Tikeraq metadyke postdates the F_3 deformation. The F_4 deformation is the only deformational phase postdating the F_3 deformation in this part of the Tikeraq srtuctural complex and the intrusion of the dyke is thought to predate the F_4 deformation which in this way may be regarded as responsible for the mentioned deflection of the foliation in the gneisses bordering the metadyke at the south coast of Tikeraq island. This assumption is supported by the apparent absence of discordant metadykes in the Agto structural complex - deformation may have obliterated original discordances.

The mineralogy, texture and field appearance of all metadykes are similar and the author believes that the dykes were intruded during the same period of basic igneous activity. If this assumption is true, they were all intruded between the deformational phases F_3 and F_4. No field evidence contradicts this view.

The field evidence shows that these dykes were intruded into rocks affected by tensional stresses and therefore they mark a cratonic phase in the history of the area. A radiometric dating programme might yield clues as to the length of this cratonic period. From the available evidence it seems reasonable to assume that the intrusion of the basic dykes marks the interval between two orogenic episodes.

Summarising, it can be stated that as the basic dykes cut migmatitic structures in the Tikeraq structural complex (fig. 3b), their intrusion postdates a long deformational history, which at least partially was contemporaneous with high grade metamorphism. The dykes themselves are affected by high grade metamorphism and deformed by regional structures, namely structures with the "typical Nagssugtoqidian trend".

The age of the gneisses and the concordant metabasites

The conclusion that the gneisses and the concordant metabasites of the Tikeraq structural complex are older than the metadykes is beyond doubt. In the Agto and the Uivfait structural complexes the same can be proved by structural arguments. If, in the Agto structural complex, rocks younger than the metadykes are present, they would be recognisable as rocks having undergone only one phase of deformation, namely F_4. However, interference patterns show that more than one phase of deformation has affected the whole structural complex. In the Uivfait structural complex the same argument may be used. Here rocks younger than the metadykes ought to have been affected by only two phases of deformation. However, at least four phases have affected the rocks.

These views on the structures and the rocks can be summarised as follows: The rocks of the whole area and the structures of the Tikeraq structural complex are older than the metadykes. If the metadykes mark a major interorogenic interval, and the author believes they do, all the rocks and the deformation phases F_{1-3} are pre-Nagssugtoqidian. The structures of the Agto structural complex represent an "aberrant" result of the Nagssugtoqidian deformational development of which the structures in the Uivfait and Nunarssuaq structural complexes are the "typical" manifestation. The principles of the structural development are summarised in fig. 8.

METAMORPHISM

General

The area is situated in the northern part of the Isortoq Complex, which is characterised by granulite facies metamorphism, and close to its northern boundary as mapped by Ramberg and Noe-Nygaard (Ramberg, 1949; Noe-Nygaard and Ramberg, 1961). The peripheral position within

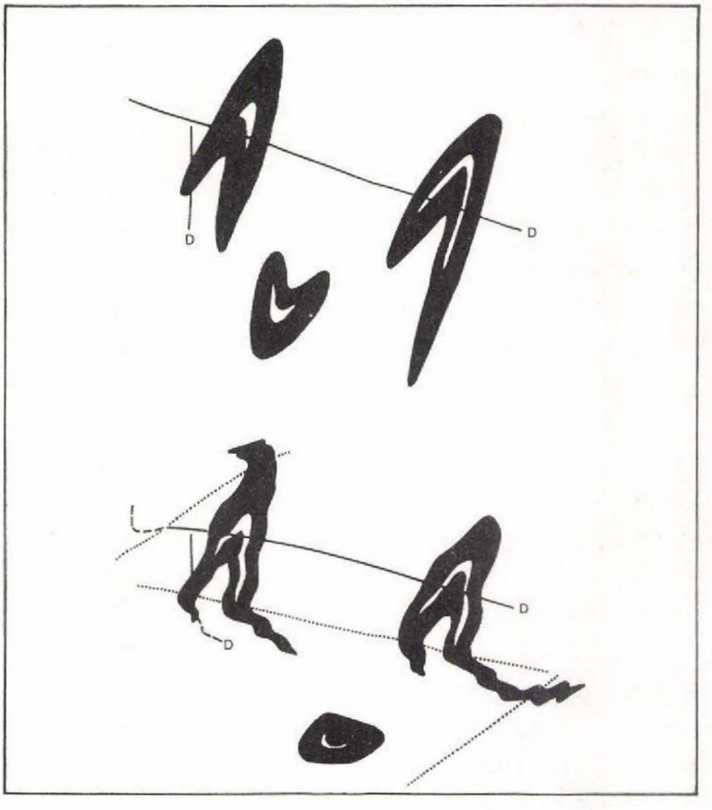

Fig. 8. Summary of the principles of the structural development in two dimensions (the horizontal plane). The upper half of the figure illustrates the type of outcrop-pattern prior to the Nagssugtoqidian orogenic activity and after the intrusion of basic dykes (D). The lower half shows the outcrop-pattern after the Nagssugtoqidian orogenic activity, using the distribution and intensity of the Nagssugtoqidian deformational phases found in the area mapped by the author. Components of pure shear are not considered. No attempt has been made to reproduce the actual outcrop-pattern.

the Isortoq Complex is reflected in the coexistence of parageneses with and without orthopyroxene. This is a common situation within granulite facies terrains and it depends on the fact that the beginning of the granulite facies is defined by a set of orthopyroxene-producing reactions whose temperature-rock-pressure equilibrium conditions depend on chemical composition, including water. Parageneses with the hydroxyl-bearing minerals biotite and hornblende and the hydroxyl-free mineral orthopyroxene are grouped in the hornblende-granulite sub-facies of the granulite facies (Fyfe et al., 1958) to which sub-facies the orthopyroxene-bearing parageneses of this area belong. The parageneses without orthopyroxene appear to have formed at the same temperature and load pressure as the orthopyroxene-bearing rocks belonging to the hornblende-granulite sub-facies (cf. Buddington, 1963, p. 1179).

Age of the metamorphism

The metamorphic state of the basic metadykes clearly shows that physical conditions leading to the formation of granulite facies parageneses acted during the part of the plutonic development postdating the intrusion of the basic dykes, i.e. during the Nagssugtoqidian orogeny.

The deformational phases postdating the intrusion of the basic dykes are called F_4 and F_5. Biotite forms axial-plane foliations to F_4 and F_5 folds. Neosome concentrations containing orthopyroxene and granitic neosome material in the migmatitic rocks are often found as axial-plane structures related to F_4 and F_5 folds, but this material recrystallised after the deformation ceased. The author is of the opinion that physical conditions suitable for high grade metamorphism acted during the deformational phases F_4 and F_5 but continued for a time after the deformation.

The faulting and accompanying shearing caused restricted downgrading of high grade assemblages. As these non-penetrative zones of movement, showing retrogressive metamorphism and cataclasis, parallel the trends of the regional structures they are thought to form an integral and late part of the plutonism and deformation of the Nagssugtoqidian orogeny.

Physical conditions during metamorphism

There are a few clues to the physical conditions acting during the peak of metamorphism: the occurrence of sillimanite, the absence of cordierite and the formation of migmatitic rocks with a granitic neosome.

The univariant equilibrium curves, sillimanite-kyanite and sillimanite-andalusite, allow a preliminary limitation to be set for the temperature-pressure conditions possible during the peak of metamorphism.

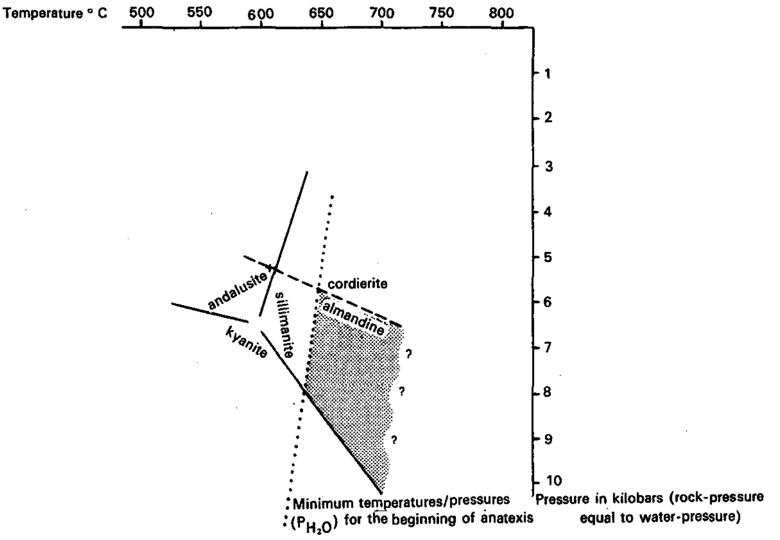

Fig. 9. Some limitations of conditions acting during the peak of metamorphism, after Winkler (1967). For further explanation see text.

The data of Althaus (1967) have been used (as also by Winkler, 1967) in drawing fig. 9. The absence of kyanite is of only little value in estimating the maximum pressure, as sillimanite at high temperatures is stable at high pressures. The formation of granitic neosome can be satisfactorily explained by assuming an in situ formation, probably anatexis. The minimum temperature at which a granitic melt forms primarily depends on the water pressure. Using the curve for the lowest temperatures at which anatexis takes place (according to Winkler, 1967) minimum temperatures can be estimated (fig. 9).

The minimum pressure acting on the rocks during the peak of metamorphism can also be estimated because of the absence of cordierite. This absence of cordierite is probably not determined by chemical composition, as sillimanite and garnet coexist in pelitic rocks. Two points on the equilibrium curve cordierite-almandine, determined by Hirschberg, are cited by Winkler (1967), and can be used to outline the highest pressures at which cordierite is stable (fig. 9). Assuming that the absence of cordierite was determined purely by physical conditions, pressures of at least 7 kilobars have acted on the rocks during metamorphism. If this pressure was due to the load of the overlying rocks the depth at which metamorphism took place was more than twenty kilometres.

SOME CONSIDERATIONS ON THE NAGSSUGTOQIDIAN OROGENY

Until the mapping of the Agto - outer Nagssutôq region started only reconnaissance mapping had been carried out in the part of the Nagssutoqidian orogeny lying south of Egedesminde. The reconnaissance mapping started in 1946, and as a result of this mapping Ramberg established the Nagssugtoqidian orogeny on the basis of the deformation and metamorphism of the Kangamiut dyke swarm (Ramberg, 1949). As mentioned in the introduction, Ramberg divided the southern part of the Nagssugtoqidian orogeny into three complexes with different grades of metamorphism but all characterised by ENE- to NE-trending structures, in this paper called the "typical Nagssugtoqidian trend".

Structural homogeneity and heterogeneity in the southern Nagssugtoqides

In the area mapped by the author structures with the "typical Nagssugtoqidian trend" are only found locally, namely in the Uivfait and Nunarssuaq structural complexes. The folds characteristic of these complexes are called F_5. These folds are of similar type and their axes vary within the axial plane depending on the varying orientation of the planar surfaces folded by F_5 (Weiss, 1955). In fig. 10 a, F_5 fold axes from the Uivfait structural complex are shown in projection. They lie in a great circle representing a plane - the "average" axial plane of the Nagssugtoqidian folds in the Uivfait structural complex. Poles to F_5 axial planes are shown to illustrate the variation in the orientation of the F_5 axial planes.

In fig. 10 b all the fold axes from the reconnaissance map by Noe-Nygaard and Ramberg (1961) from Disko Bugt to the southern boundary of the Nagssugtoqidian orogenic belt are shown. These folds are of course of different ages, but nevertheless this projection on the whole is similar to fig. 10 a. As fig. 10 a represents an area of less than 2 km^2 and fig. 10 b more than 20 000 km^2, it may be suggested that whatever irregularities may be present in fig. 10 b, homogeneity with respect to some structural elements is characteristic of the southern part of the Nagssugtoqidian orogenic belt.

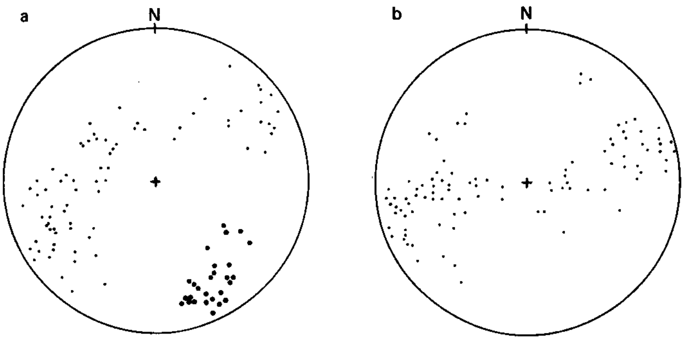

Fig. 10. a: Lower hemisphere, equal area projection of F_5 fold axes from the Uivfait structural complex and some related axial planes (heavy dots). b: Projection of all fold axes from the part of the Nagssugtoqidian orogenic belt lying south of Disko Bugt, taken from the reconnaissance map by Noe-Nygaard and Ramberg (1961). For further explanation see text.

From the description of the area mapped by the author it is clear, however, that the degree of deformation due to F_4 and F_5 is very variable, with the result that old structures were preserved in the Tikeraq structural complex and F_4 structures in the Agto structural complex.

In the Agto - Nagssugtôq region the development of the ENE- to NE-trending structures varies also on a large scale. Belts of large scale transposition, characterised by ENE-striking lithologic units, alternate with belts where folding is of a more gentle type resulting in easily detectable interference patterns. This alternation is without doubt a most interesting aspect of the Nagssugtoqidian orogeny and is readily observed on aerial photographs. It was observed by Noe-Nygaard and Berthelsen (1952), but they assumed that the difference in tectonic style between the north coast and the south coast of Nagssugtôq was due to differences in axial plunges, but as the axial plunges are a function of the earlier structures, and as the belts of "equal tectonic style" are parallel to the Nagssugtoqidian trend, we can conclude that it is the character of the Nagssugtoqidian deformation which changes. Escher (1966) has also observed this heterogeneity in his reconnaissance mapping. Future work and future considerations on Nagssugtoqidian geology must necessarily focus on this aspect.

The aerial photographs show that the belts of similar tectonic style cross the boundary between the Isortoq and Egedesminde Complexes in the central part of Nagssugtôq. These observations do not support the proposal by Noe-Nygaard and Berthelsen (1952) that the structures of the amphibolite and granulite facies terrains differ.

The age of the rocks

It has been shown that the gneisses of sedimentary origin as well as of unknown origin in the area around Agto are probably of pre-Nagssugtoqidian age (using the intrusion of the basic dykes as time-divider). This could be shown by structural arguments. These arguments may also be used for the metasedimentary rocks occurring in the rest of the Agto - outer Nagssugtôq region. South of Nagssugtôq metasedimentary rocks form interference patterns of varying types (see the map in Noe-Nygaard and Berthelsen, 1952) and it seems probable that these structures are as composite as those in the area mapped by the author.

Three K/Ar dates of biotite from the southern part of the Nagssugtoqidian orogenic belt have been published (Larsen and Møller, 1968). In million years they are: 1710 ± 30 from Nagssugtôq, 1650 ± 40 from Agto and 1740 ± 30 from the Egedesminde district. One K/Ar whole-rock age determination for pseudotachylite (Jensen, 1968) from the Agto district gave 3070 ± 70 m.y. (Larsen, 1969). Whatever speculations may arise from this age, it is certainly not in any way contradictory to the view that at least some of the rocks in the region are of pre-Nagssutoqidian age.

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