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Tectonic displacements and thermal activity in two contrasting Proterozoic mobile belts from Greenland

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The Proterozoic Nagssugtoqidian and Ketilidian mobile belts are comparable in scale with those of the Phanerozoic rather than those of the Archaean. These two Proterozoic belts differ from one another both in the tectonic displacements which gave rise to them, and in their thermal activities as expressed by igneous and metamorphic characteristics. Similar differences between modern tectonic belts have been interpreted in terms of plate tectonics. The Nagssugtoqidian is characterized by considerable crustal shortening, very limited igneous activity, and high-pressure regional metamorphism which may be related to crustal thickening resulting from both ductile and brittle overthrusting of the Nagssugtoqidian rocks over the Archaean foreland. Evidence of crustal shortening in the Ketilidian is limited, but vertical and transcurrent movements are important. Widespread igneous activity throughout the active history of the belt resulted in the formation of mainly acid volcanic supracrustal rocks and widespread granite intrusion. The appinite suite is also well represented. Metamorphism is mainly of low-pressure type. A tentative comparison can be made between the Alpine and Nagssugtoqidian belts on the one hand, and Andean and Ketilidian belts on the other.

Introduction

The Nagssugtoqidian and Ketilidian mobile belts which lie respectively north and south of a central block of Archaean gneisses in Greenland (figure 1) represent large areas of the crust either formed or highly modified during the Proterozoic. Their boundaries – each of which extends for over 400 km in Greenland and which must extend into Canada and Europe – represent major crustal features comparable in scale to the boundaries of Cenozoic mobile belts. Distinct tectonic provinces of the types described, with boundaries extending on a continental scale, have not been reported from the Archaean and we suggest that their presence in the Proterozoic may represent fundamental changes in crustal character – perhaps reflecting the development of tectonic régimes in the crust and mantle comparable in scale to those operative at the present time.

It is usual in the current development of geological thought to consider major areas of Phanerozoic crustal mobility in terms of the movement of plates, and a knowledge of the relative displacement across the boundaries of modern tectonic provinces is assumed even when it has not been observed directly. One of the main objects of this paper is to present evidence and opinions about the type and scale of movements associated with the formation of the Nagssugtoqidian and Ketilidian mobile belts in terms which allow comparison with more recent mobile belts. Secondly, it has also become customary to associate the different types of igneous and metamorphic assemblages found within modern mobile belts, with the interaction of crustal and mantle material in the different tectonic environments which result from the movement of plates. It appears to us that the very different metamorphic and igneous characters displayed by the two Proterozoic mobile belts summarized here can be described in the same terms as possible modern counterparts, provided that the parameters chosen are regional and do not represent superficial characters such as erosion level. We consider that perhaps the two most useful characters which can be used to compare Precambrian mobile belts with possible modern analogues are the tectonic displacement of rocks within the mobile belts compared to those in the bordering basement areas, and secondly thermal activity within the belts as reflected by the types of magmatic activity and overall metamorphic characters displayed.

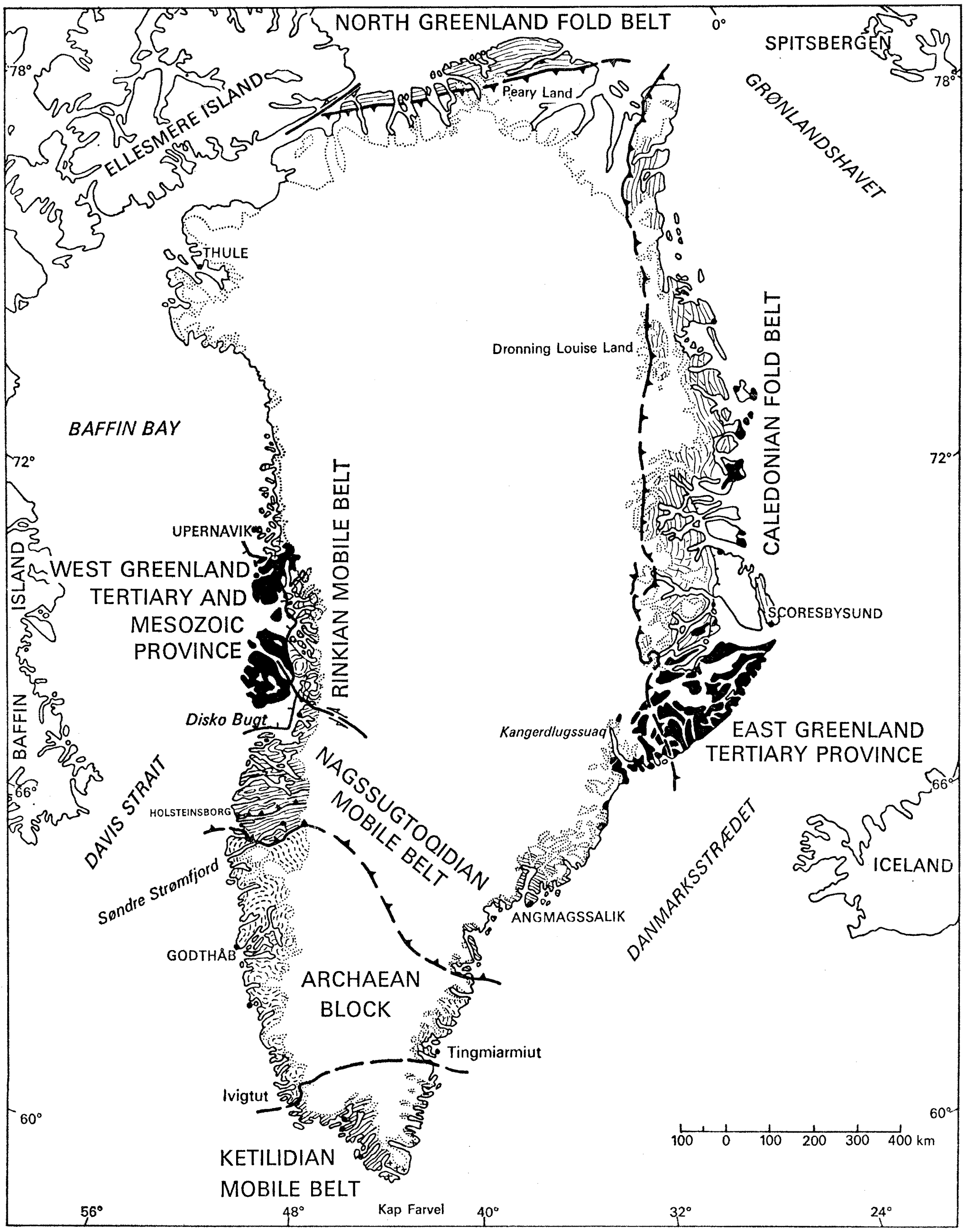


Figure 1. The main geological divisions in Greenland.

The Nagssugtoqidian mobile belt

The gneisses forming the northern part of the Archaean block in East and West Greenland are cut by dense swarms of dolerite dykes. Towards the north the dykes, together with their country rocks, are progressively deformed and metamorphosed resulting in a reorientation and parallelization of both dykes and country rock structures. These changes were the basis on which Ramberg (1949) distinguished a Nagssugtoqidian complex from a pre-Nagssugtoqidian (Archaean) complex in West Greenland. Similar observations by Bridgwater & Gormsen (1968) in southeast Greenland made it possible to correlate the Nagssugtoqidian mobile belt from West to East Greenland. It forms a *ca.* 300 km wide belt characterized by a pronounced regional fabric oriented parallel to its boundary with the Archaean block (figure 1). In West Greenland this regional fabric is cut to the north by the wrench fault zone which separates the Nagssugtoqidian from the Rinkian mobile belt. Although K/Ar dating of Nagssugtoqidian rocks gives ages within the range 1790 to 1650 Ma (Larsen & Møller 1968) preliminary U/Pb dating of recrystallized zircons by R. Chessex (personal communication, 1971) suggests that the main phase of Nagssugtoqidian deformation and metamorphism is much older and probably took place at the beginning of the Proterozoic.

The Nagssugtoqidian mobile belt in West Greenland

Stratigraphy and lithology

The Nagssugtoqidian rocks consist mainly of reworked Archaean basement gneisses, locally with interlayered and folded relics of Archaean and early Proterozoic supracrustals.

The reworked gneisses are mostly granodioritic to quartz-dioritic containing biotite, hornblende and garnet. Hypersthene is often present in the central part of the belt. Basic layers, lenses and agmatites are common. In the southern part of the Nagssugtoqidian belt these basic fragments are believed mainly to represent reoriented and metamorphosed remnants of dolerite dykes belonging to the same dense swarms which intruded the Archaean gneisses south of the boundary.

Supracrustal rocks, largely represented by metasediments, occur mostly in the central and northern part of the Nagssugtoqidian belt, north of the Holsteinsborg thrust fault (Henderson 1969; Bondesen 1970; Sørensen 1970; Bek 1970). They form thin belts interlayered and deformed together with the basement gneisses. Nowhere has a basal unconformity been recognized, the original contact always having been obliterated by later movements. Two main groups of supracrustal rocks can be distinguished:

(*a*) An older Archaean group, showing evidence of having been metamorphosed and strongly deformed in pre-Nagssugtoqidian times. It is composed mainly of sillimanite-bearing garnet–biotite gneisses containing locally very thin bands of impure marbles and calc-silicates. Graphite appears to be rare in these early metasedimentary rocks.

(*b*) A younger group, formed in the time interval separating the last main Archaean period of metamorphism from the first Nagssugtoqidian metamorphic event. North of the Holsteinsborg thrust fault it is composed mostly of marbles, quartzites and calc-silicate rocks associated with graphite-schists containing sillimanite, garnet and muscovite. In the southern part of the belt, south of the Holsteinsborg thrust zone only a few occurrences of younger supracrustals were found. They consist mainly of anthophyllite schists, phyllites, amphibolites and marbles. Relict pillow structures have been recognized locally in these southern rocks.

No large granite areas occur within the Nagssugtoqidian in West Greenland, although a few small isolated granites associated with migmatites have been observed. These appear to be synkinematic with the main Nagssugtoqidian deformation. A large folded quartz diorite body is found in the central part of the belt (Henderson 1969). The main part of the body is homogeneous containing hypersthene, hornblende and biotite. At the margins it passes into a dark biotite–garnet gneiss. It is considered to have been a thick, very extensive intrusive sheet, which has undergone Nagssugtoqidian deformation and metamorphism. Its age is possibly early Nagssugtoqidian.

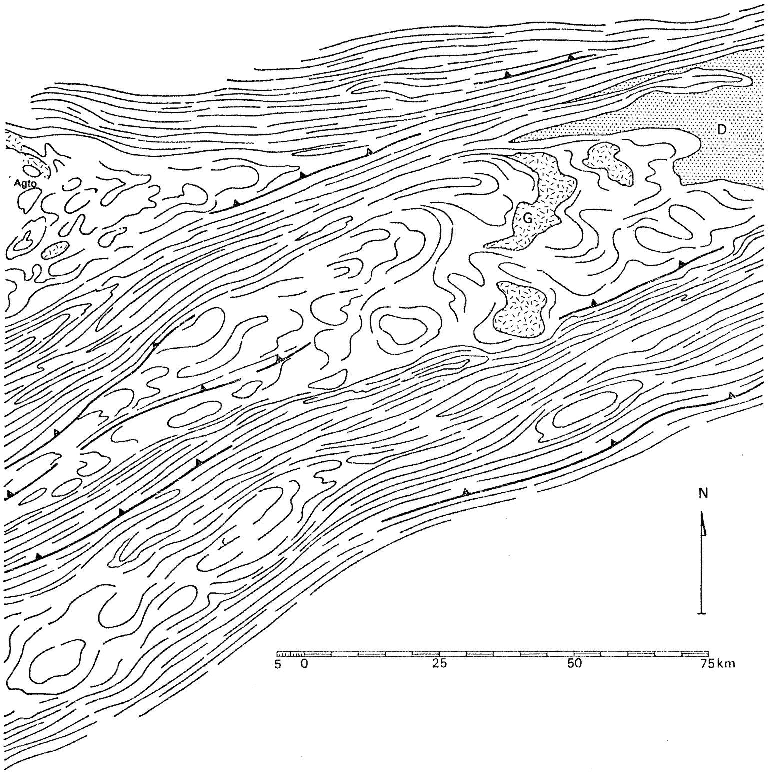


FIGURE 2. Structural pattern of alternating linear belts and less deformed areas in the central part of the Nagssugtoqidian mobile belt in West Greenland. G = granite, D = quartz diorite.

Structure and metamorphism

As observed by Ramberg (1949) and Noe-Nygaard (1952) the Nagssugtoqidian complex is characterized in West Greenland by a predominant northeast trend of the main structural elements. In a general way it is possible to subdivide the complex into linear or straight belts where this regional fabric is well developed, and areas where a preferred direction is not so obvious (figure 2). This typical alternating pattern resembles a large-scale augen structure. The augen are represented by the lens-shaped lacunae in which the original Archaean structures and the dykes intruding them are best preserved. In contrast the Archaean structures and later dykes in the linear belts are generally completely deformed and reoriented by the later Nagssugtoqidian movements. Detailed studies by Bondesen (1970), Sørensen (1970) and Skjernaa (in preparation) in the Agto region show that the Archaean 'lacunae' possess intricate basin and dome structures formed by superimposed similar-type folding (figure 3). This structural pattern, lacking any dominant strain direction, is very similar to that found in the main

Archaean block south of the Nagssugtoqidian boundary. In the linear belts, the pronounced ENE trend is probably due to a dominant Nagssugtoqidian simple shear strain. This mainly rotational strain acted partly in a horizontal direction parallel to the linear belt (Sørensen 1970), and partly upwards and at right angles to the belt, along shear planes dipping to the NNW. The contact between linear belts and Archaean lacunae can be progressive, due to ductile shear, or discordant due to brittle thrusting (Platou 1970). The planes of thrusting and shear generally dip between 30 and 55° to the NNW. In many places, and particularly in the northern part of the Nagssugtoqidian mobile belt, the linear belts are deformed by a weak late-Nagssugtoquidian deformation, resulting in large open folds and flexures with northwest striking axial surfaces.

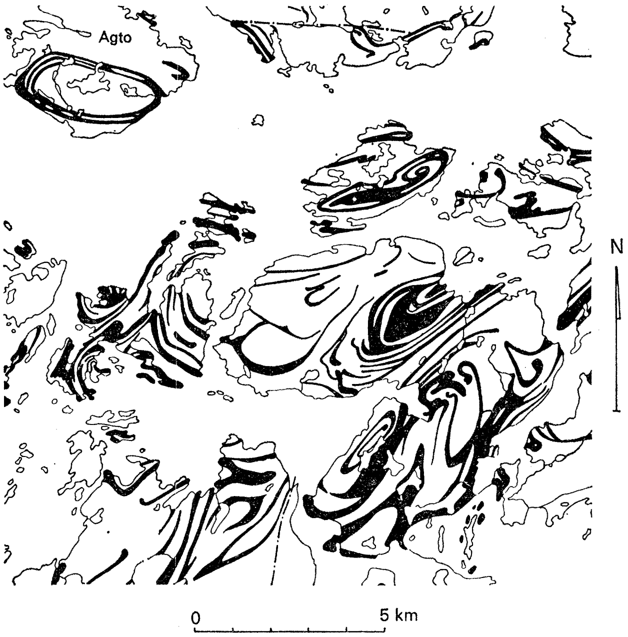


FIGURE 3. Intricate basin and dome structures formed by superimposed similar-type folding in the Agto region. (From Bondesen 1970.)

In the southern part of the mobile belt the Nagssugtoqidian deformation was accompanied by a retrogression of the Archaean granulite facies gneisses to amphibolite facies. In the central part of the belt granulite facies and amphibolite facies rocks co-existed during the Nagssugtoqidian deformation, the differences in metamorphic facies being probably due to local variations in original composition and water pressure of the rocks (Sørensen 1970). There are only a few clues to the physical conditions during the peak of metamorphism. However, the occurrence of sillimanite and the absence of cordierite throughout the Nagssugtoqidian of West Greenland shows that the pressure may have been relatively high.

The southern Nagssugtoqidian boundary

The southern Nagssugtoqidian boundary in West Greenland cuts across Søndre Strømfjord near the Sukkertoppen ice cap, following roughly an ENE direction. South of this boundary, granulite facies gneisses are cut by two undeformed basic dyke swarms, with a dominant ENE striking swarm (the Kangâmiut dyke swarm) post-dating an east–west swarm. The Nagssugtoqidian boundary is in this area a transition zone approximately 20 km wide in which

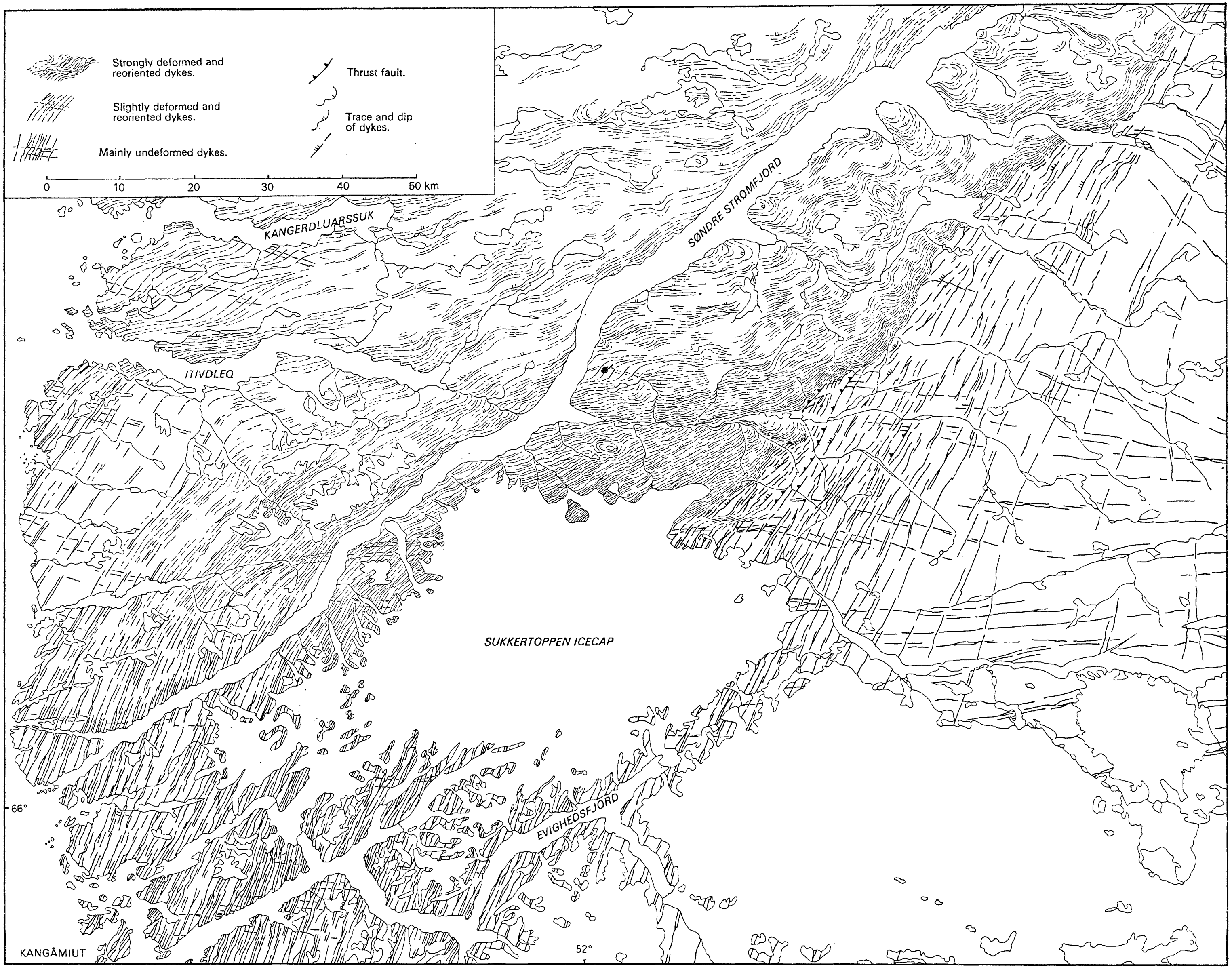


FIGURE 4. Map of the deformed and undeformed dykes in the Søndre Strømfjord area.

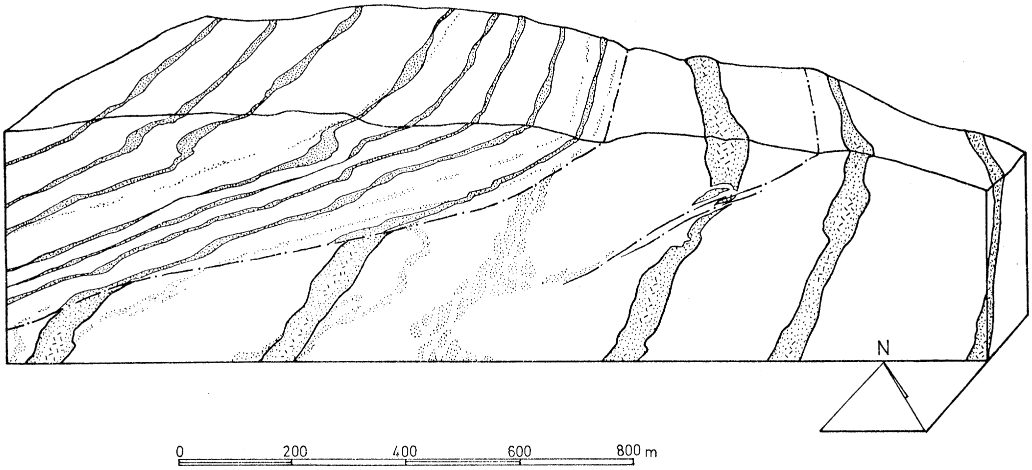


FIGURE 5. The main Nagssugtoqidian deformation boundary in the region northeast of the Sukkertoppen icecap: both dykes and gneiss structures are deformed and reoriented by a ductile overthrusting (rotational or simple shear strain) from the NNW.

retrogression of the granulite facies gneisses takes place progressively. The mineralogical changes are closely correlated with structural changes, the most dramatic of which is a change in strike and dip of both dyke swarms (figures 4, 5). This change can either be abrupt, or more gradual and brought about by a series of parallel shear belts.

The deformation of two dyke swarms, which were originally at a high angle to one another, affords an ideal circumstance for measuring the post-dyke deformation of the area lying to the north of the boundary. Results so far obtained (Escher, Escher & Watterson 1972) show that the boundary represents the southern limit of rocks which have undergone intense rotational homogeneous strain, or simple shear strain. The strain ellipsoid representing the Nagssugtoqidian deformation is a plane strain type with an $X:Z$ axial ratio of about 50:1. The plane of simple shear to which the boundary is parallel dips NNW at 10 to 20°, with the direction of simple shear within this plane being SSE. The type of movement involved is of the type illustrated in figure 6. This type and amount of strain can be regarded as effecting an overthrusting of the northern amphibolite facies, onto the southern granulite facies block with an effective horizontal shortening of at least 65 %. Although horizontal shortening by this mechanism cannot take place without some relative vertical displacement of the rocks on either side of the boundary, the vertical movement is insignificant relative to the horizontal displacement.

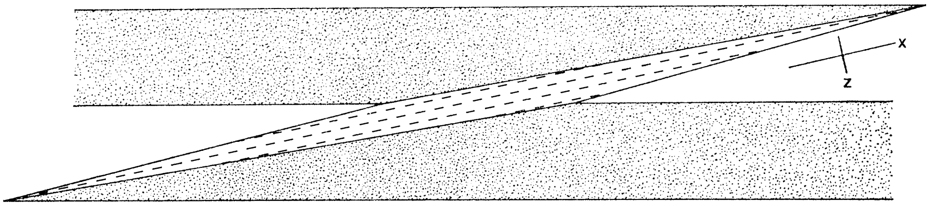


FIGURE 6. Crustal shortening by simple shear mechanism resulting in sub-horizontal stretching direction (X axis), lying within foliation (XY plane) shown by broken lines. Vertical section, not to scale.

The displacement at this boundary can be described as ductile overthrusting of the Nagssugtoqidian rocks over a stable Archaean foreland. The total amount of shortening cannot be established without a better knowledge of Nagssugtoqidian rocks further removed from the boundary, but must exceed, probably greatly, 100 km.

A notable feature of the boundary and region to the north is the lack of igneous activity except that represented by the basic dyke swarms, which are thought to have been emplaced immediately prior to the ductile deformation.

A geometric consequence of the type and amount of strain described is that although there is considerable horizontal shortening, the stretching direction of the rock fabric, i.e. the X axis of the strain ellipsoid, is sub-horizontal. Conversely, the direction of shortening (Z axis) is subvertical. These relationships, which at first sight are surprising, are a consequence of the very small extension field (about 10°) in a 50:1 ellipse.

Conclusions

There seems to be in principle no difference between the southern Nagssugtoqidian boundary and the boundaries within the mobile belt between less reworked Archaean lacunae and strongly reworked linear belts. Both probably reflect a considerable shortening of the crust, brought about by a succession of imbricate shear zones and thrusts dipping to the NNW. This may have been caused by a maximum principal stress alined NNW–SSE and causing a large-scale overthrusting of the Nagssugtoqidian region over the Archaean block to the south. The overthrusting being partly ductile and partly brittle depending on the state of the material or on the rate of deformation. It seems that the main mechanism of deformation which acted throughout the Nagssugtoqidian was a homogeneous simple shear strain. The less reworked lacunae of Archaean rocks within the mobile belt possibly represent originally more competent zones.

The difference in type of supracrustal rocks between the areas north and south of the Holsteinsborg thrust may imply a fundamental difference between these areas prior to Nagssugtoqidian events.

The Nagssugtoqidian mobile belt in East Greenland

The formation of the Nagssugtoqidian on the east coast appears to have been effected by the same major geological controls as that on the west coast. South of the boundary the Archaean rocks consist of amphibolite facies gneisses, with patches of cordierite granulite facies rocks developed locally (Bridgwater, Watson & Windley, this volume, p. 493). The gneisses are cut by several generations of basic dykes comparable with those seen on the west coast, although never reaching the same volume of intruded material outside the area affected by younger deformation.

North of the Nagssugtoqidian boundary both the Archaean gneisses and the dykes cutting them are involved in at least two phases of Proterozoic deformation which are concentrated in well-defined belts trending approximately east–west and dipping 20 to 30° towards the north. There is some evidence that both the post-dyke deformation and the intrusion of the dykes themselves were controlled by earlier late Archaean–early Proterozoic shear zones (Bridgwater, Escher & Watterson 1972) and that the boundary was a zone of active movement for some considerable time before and after the injection of the dykes.

Between the belts of strong deformation there are lacunae of gneiss in which the original Archaean structures and the basic dykes intruding them are well preserved. These lacunae vary in size from rounded 'inclusions' of recognizable Archaean rocks (such as gabbro anorthosite) preserving their original textures (see figure 2 of Bridgwater *et al.* this volume, p. 506) to major mappable units tens or even hundreds of square kilometres in area. The belts show a marked change in character from the southern contact of the reworked area near Gyldenløves fiord northwards. In the south the belts are narrow (generally less than 1 km) and show well-defined contacts. The rocks within them show extreme deformation, all original textures are destroyed and discordant structures such as the dykes are rotated completely parallel to those of the gneiss. The gneisses themselves take on a very strong schistosity and break like slates. On air photographs and from a few tens of metres in the field they appear like phyllitic horizons, although derived from inhomogeneous granitic gneisses. Both the dykes and the gneisses have recrystallized in greenschist – low amphibolite facies conditions, with copious epidote and chlorite developed. Outside the belts many of the dykes show their original igneous mineralogy and texture. In detail, margins of the shear belts commonly show an imbricate structure. Rocks within the belts commonly develop a strong linear fabric plunging in the plane of the schistosity at 10 to 30° to the WNW and NNW. In general the NNW linear structure appears earlier but there are exceptions, and it appears that the belts of deformed rocks have acted as planes of weakness during several periods of post-dyke movement. In spite of the extreme deformation in the belts, originally discordant structures such as the dykes are continuous from the undeformed areas into the deformed belts, although rotated parallel to the new structures. For this to occur as a general feature implies simple shear comparable to the mechanism proposed for the west coast, rather than flattening by pure shear.

50 to 150 km north of the boundary the belts of post-dyke deformation become broader, less well defined, and the grade of metamorphism associated with their formation increases. Nappe structures are locally seen. Kyanite is found alined along the plunge of the NNW linear structures and is one of the major rock-forming minerals in the pelitic gneisses to the west of Angmagssalik. This mineral has only been reported in minor amounts in the Archaean of Greenland and its presence in large quantities in reworked Archaean pelites can reasonably be ascribed to a marked increase in pressure presumably associated with the deformation described here. The dykes are recrystallized to garnet amphibolites. Some of the basic bodies involved in the deformed belts have recrystallized into rounded masses containing centres of pyrope-rich garnet and a green diopside. These are not true eclogites since the sodium content of the pyroxene is low, but their presence within the Nagssugtoqidian belt is taken to show the development of moderately high pressures.

Following the formation of the major deformation belts the rocks 150 km north of the boundary were intruded by a series of calc-alkaline rocks varying from norites to granodiorites and adamellites. They were accompanied by numerous pegmatite swarms. A general late rise of isotherms in the area is marked by the partial replacement of kyanite by sillimanite.

As on the west coast, the regional relationships on the east coast can be interpreted as a contact between two major blocks, the southern block being overridden by the northern along a series of thrusts. The general direction of movement of the northern block shown by the marked linear features has been from the north and west. It probably occurred in at least two stages after the intrusion of the dykes. No estimates of the amount of movement involved have been made, partly because of the reconnaissance nature of the mapping in the area and partly because of the complications due to more than one phase of movement after the intrusion of the dyke. However, it appears that the total amount of deformation is comparable with that seen on the west coast, and that the movements involved are in the same direction and are probably similar. The differences between the two coasts may be partly explained by differences in erosion level. The southernmost belts of Nagssugtoqidian deformation on the east coast may represent a higher level on the original front than that exposed on the west coast.

The Ketilidian mobile belt

A brief inspection of the tectonic/geological map of Greenland (Escher 1970) shows that the southern tip of Greenland differs markedly from other Precambrian areas on the island in the amount of massive intrusive granites exposed. Igneous and tectonic activity occurred in the area over a period of at least 1000 Ma and may have lasted for 1500 Ma (Bridgwater, Escher & Watterson 1972). During this long period the area now forming south Greenland appears to have been one of exceptionally high thermal activity suggesting the presence of a deep-seated heat source in the mantle.

The main metamorphic event so far dated from south Greenland occurred about 1830 Ma ago (Gulson & Krogh 1972). This is regarded as the youngest high-grade regional metamorphism in a complex sequence of magmatic, tectonic, and metamorphic events, post-dating the deposition of Proterozoic supracrustal rocks on an older Archaean basement preserved to the north. No isotopic evidence for the presence of this basement south of the border zone has yet been obtained and it appears that the metamorphic event dated at about 1830 Ma has effectively reset most of the isotope systems in the rocks within the major part of the fold belt. The high grade metamorphism was followed in the southernmost part of Greenland by the intrusion of a suite of post-tectonic norites, quartz monzonites and rapakivi granites dated between 1774 and 1786 Ma, and nearer the border of the fold belt by regional pegmatite swarms, adamellitic granites and the youngest of a widespread group of hornblende diorites and associated intermediate rocks collectively termed the appinite suite. General uplift marked by the closure of the Rb/Sr and K/Ar mineral systems occurred around 1500 to 1600 Ma ago. Sinistral wrench faulting, the deposition of graben-controlled continental sandstones, and the intrusion of major dyke swarms accompanied by the emplacement of the plutonic centres of the Gardar alkali province, marked the final stages of Precambrian thermal activity in the area between 1400 and 1000 Ma ago.

The anatomy of the mobile belt

For descriptive purposes the Ketilidian mobile belt can be subdivided into a number of zones from the margin of the belt inwards (figure 7): (1) a marginal zone in which Archaean basement rocks and an overlying cover of Proterozoic sediments are progressively involved in Proterozoic metamorphism (Henriksen 1969); (2) a granite zone, the Julianehåb granite, a complex batholith of granites, diorites and granitic gneisses; (3) a complexly folded migmatite zone of granites, granitic gneisses and migmatized Proterozoic sediments generally with complex structures and amphibolite facies mineralogy; (4) a flat-lying migmatite complex consisting of high grade (cordierite–amphibolite to cordierite–granulite facies) meta supracrustal rock, granite sheets and numerous late intrusions.

The marginal zone of the Ketilidian mobile belt

The marginal zone of the mobile belt (figure 8) is best known from the Ivigtut area of west Greenland where its general features have been well documented by Higgins, Bondesen, Henriksen and Jensen, in Windley *et al.* (1966) and by Henriksen (1969). In the Midternaes–Graenseland areas northeast of Ivigtut (*ca.* 61° 30′ N) peneplained Archaean gneisses and metasupracrustal rocks are overlain by a minimum thickness of 6000 m of Proterozoic sediments and tholeiitic volcanics (Higgins 1970; Bondesen 1970).

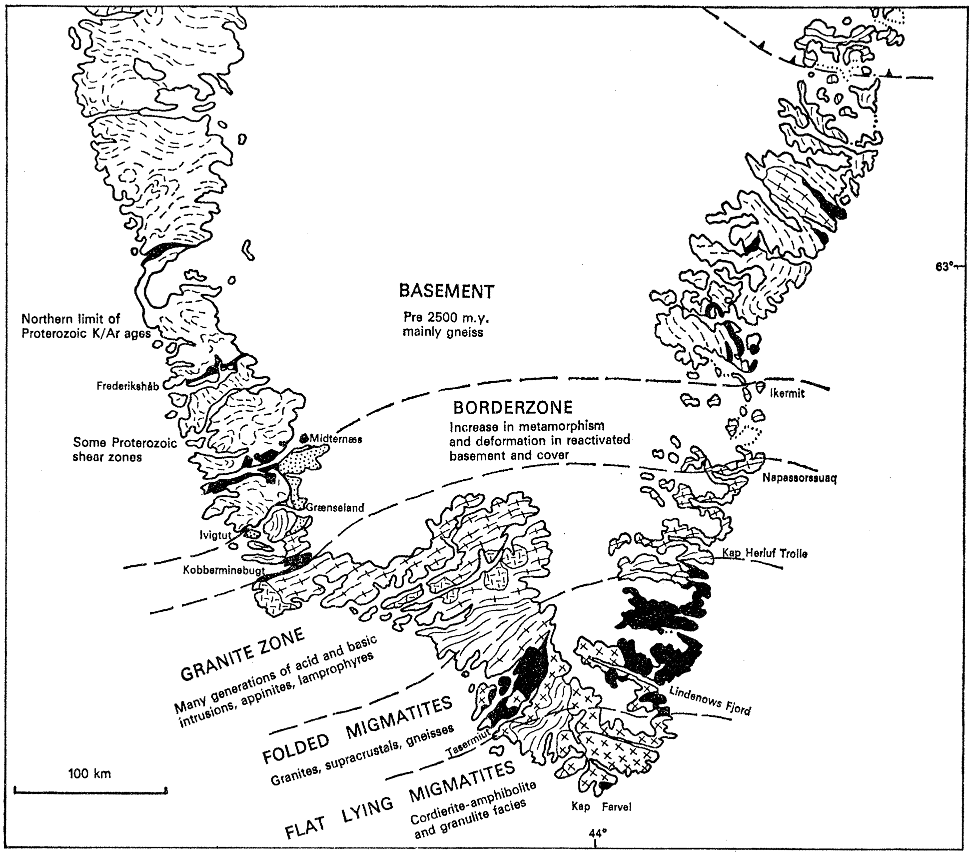
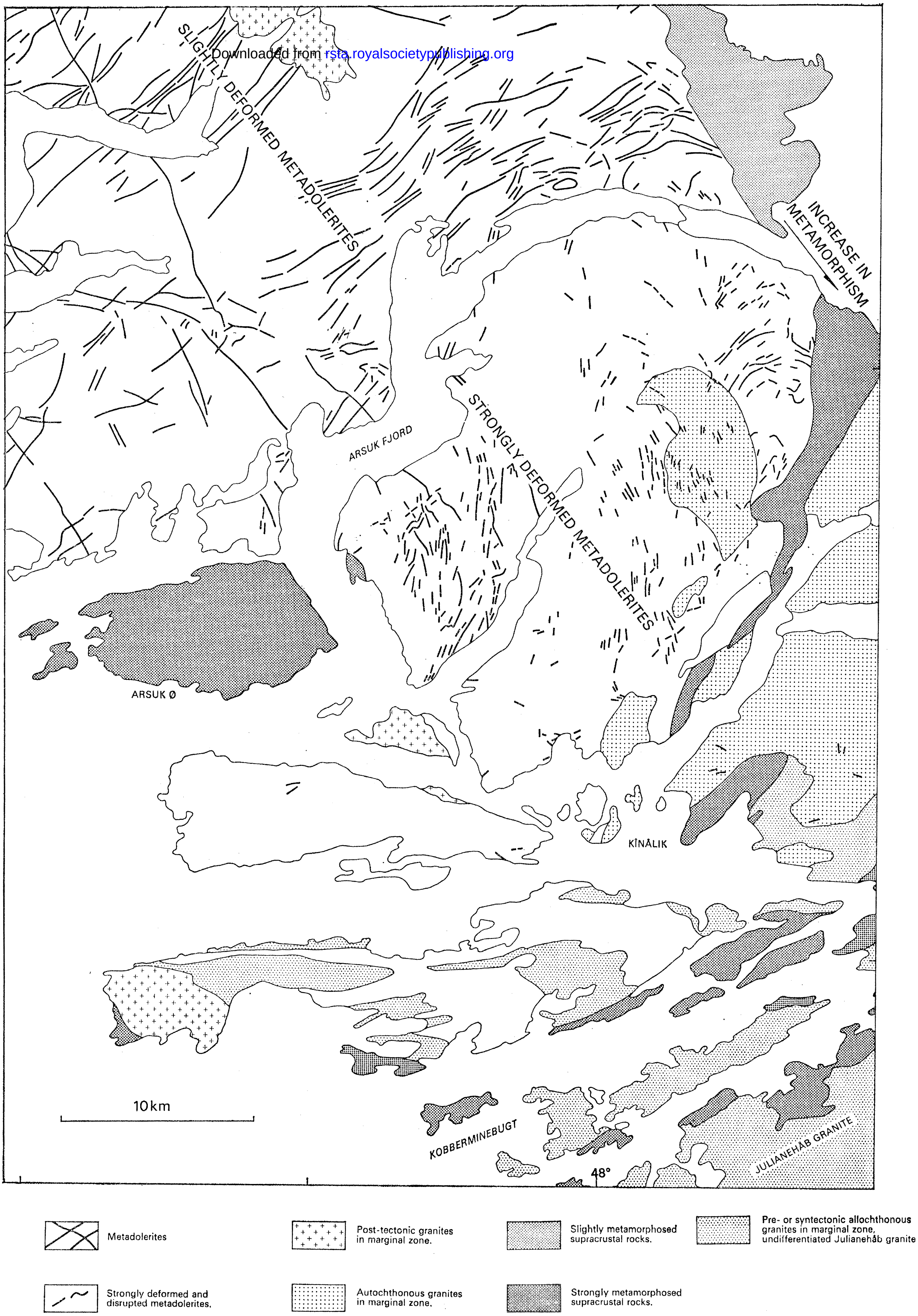


Figure 7. The main geological divisions of the Ketilidian mobile belt.

Traced southwards over a distance of 50 km the original unconformity is gradually destroyed first by thrusting and then by rotation of the basement and cover structures into parallelism. Both basement and cover rocks are metamorphosed under low to medium pressure, medium to high temperature amphibolite facies conditions with the formation of andalusite, sillimanite, staurolite and garnet. Post-Archaean basic dykes in the basement rocks show a transition from northwest to southeast, changing from dolerites with slightly sheared margins to lineated and disrupted amphibolite layers in partially remobilized gneiss (Bondesen & Henriksen 1965). Large areas of autochthonous and para-autochthonous granite develop in the basement gneisses particularly near to the contacts of the supracrustal units. In the southeastern part of the Ivigtut area major bodies of allochthonous granites were intruded into the gneisses and supracrustal rocks breaking up the latter into a series of discontinuous units. The structures in the border zone of the mobile belt suggest that some compression occurred in the area with thrusting of the upper parts of the supracrustal successions from the south and east over the lower units and the old basement. The basement-cover contact was rotated from approximately north to south with a shallow easterly dip, to east to west with a steep dip to the south in the Kobberminebugt area. Both basement and cover from part of a major fold structure in the southern part of the Ivigtut area with an axis plunging to the WSW at a shallow angle. Total crustal shortening in the border zone shown by the formation of this structure can reasonably be estimated to be of the order of several tens of kilometres in a general SSE to NNW direction. This shortening has occurred without extreme deformation of any particular unit in the basement or cover except along local


SLIGHTLY DEFORMED METADOLERITES
INCREASE IN METAMORPHISM
STRONGLY DEFORMED METADOLERITES
ARSUK FJORD
ARSUK Ø
KÎNALIK
KOBBERMINEBUGT
JULIANEHÅB GRANITE
10 km
48°
Metadolerites
Strongly deformed and disrupted metadolerites.
Post-tectonic granites in marginal zone.
Autochthonous granites in marginal zone.
Slightly metamorphosed supracrustal rocks.
Strongly metamorphosed supracrustal rocks.
Pre- or syntectonic allochthonous granites in marginal zone, undifferentiated Julianehåb granite

thrust planes and along the actual contact of originally discordant structures. Original lithological units have remained intact. This phenomena, together with the general grade of metamorphism and the amount of granitic material in the border zone, suggest to us that the deformation was essentially ductile.

On the east coast the marginal zone is represented by a flat-lying sequence of migmatized metasupracrustal rocks intercalated with granitic gneisses and intrusive granite sheets, overlying an older basement (Andrews, Bridgwater, Gulson & Watterson 1971). No structures suggesting that there was major tectonic transport of material have been observed.

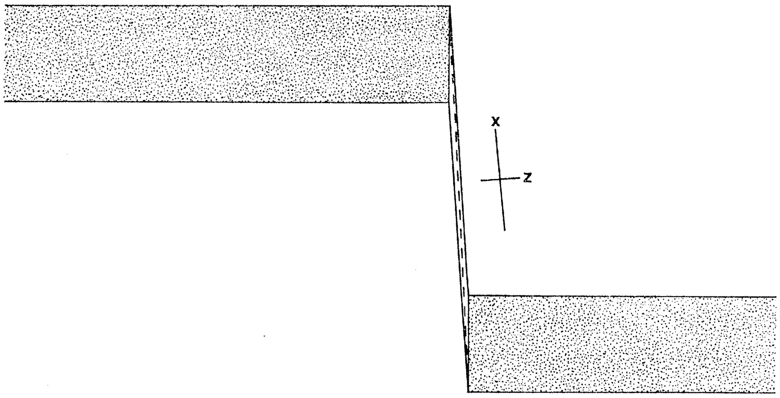


FIGURE 9. Vertical or transcurrent crustal displacement by simple shear mechanism, resulting in steep foliation (broken lines) and subhorizontal shortening axis (Z). Sketch can be read as either vertical section (vertical displacement) or horizontal section (transcurrent displacement). Not to scale.

At the southern limit of the marginal zone the Ketilidian granites and supracrustal rocks are involved in a belt of high deformation 5 to 15 km broad and striking ENE, along Kobberminebugt, parallel to the general trend of the mobile belt. A similar structure has been noted along strike on the east coast at Napassorssuaq fiord. The main structures observed in this belt were formed fairly late in the sequence of events recorded from the mobile belt, after the deposition and initial metamorphism and folding of the supracrustal rocks and their intrusion by granites, but before the emplacement of the youngest granitic complexes. We consider it possible, however, that this steep structure and others similar to it found farther south may have been initiated very early in the history of the mobile belt and may have controlled the original distribution of supracrustal rocks and the emplacement of the earliest Ketilidian granites. The Kobberminebugt belt marks a fundamental change in lithology; neither supracrustal rocks demonstrably equivalent to the supracrustal sequences in the border zone, nor gneisses derived from an Archaean basement of the type exposed farther to the north, have been identified with any certainty south of Kobberminebugt.

The data available from the Kobberminebugt belt of high deformation (Watterson 1965) shows that the foliation, corresponding to the XY plane of the strain ellipsoid, is subvertical striking on average at 70° with a steep dip towards the south. From figure 9 it can be seen that a subvertical foliation is consistent with either a vertical or transcurrent displacement by a simple shear mechanism. The fact that the shortening direction (Z axis) of the rock fabric is subhorizontal and normal to the boundary need not imply that major crustal shortening normal to the boundary is involved. The existence of deformed enclaves with $X{:}Z$ ratios of

1:400 (Watterson 1965, p. 53) shows that, at least locally, deformation was as intense as that in the Nagssugtoqidian.

In the Kobberminebugt area, the stretching direction of the fabric (X axis) is subhorizontal within the steep foliation, suggesting that the displacement was there transcurrent rather than vertical.

The granitic zone

A 50 km wide belt of granitic rocks known as the Julianehåb granite, of general intrusive aspect and overall granodioritic to adamellitic composition, extends ENE from Julianehåb Bay on the west coast to Napassorssuaq on the east coast. Early members of the granitic suite are involved in the Kobberminebugt–Napassorssuaq fiord deformation zone and in a corresponding subvertical structure on the south of the body trending ENE to the south of Julianehåb. The pluton contains many different generations of igneous rocks varying from hypersthene diorites, appinites and rare ultrabasic masses to granodiorites, adamellites and microcline granites. Large inclusions of migmatitic gneisses and metamorphosed supracrustal rocks occur within the body. The migmatitic inclusions do not show any marked resemblance to the Archaean basement rocks and the majority could be interpreted as derived from an early sequence of migmatized Proterozoic supracrustal rocks. The recognizable inclusions of supracrustal rock are generally basic or acid tuffs and agglomerates, some of which are in a remarkably good state of preservation. It seems quite possible that these may represent a volcanic sequence originally capping the batholith, which has been preserved as stoped blocks.

Three characters of the Julianehåb granite are of importance to discussion of the development of the mobile belt:

(1) The marked petrological similarity of the Julianehåb granite to suites in more recent batholithic masses such as the coastal batholith of Peru and Chile. This similarity is particularly marked in the hornblendic intermediate and basic rocks and in the relationships between acid and basic parts of the pluton. Many of the characters described from the Peruvian batholith at the recent Geological Society of London meeting (1972) are present in the Julianehåb granite (see, for example, papers by Allaart (1967) and Watterson (1968)).

(2) The widespread deformation of the pluton – many of the early members of the intrusive suite show a well-marked vertical foliation trending approximately ENE parallel to the margin of the pluton and to the general trend of the mobile belt. No regional measurements of the direction or amount of maximum principal strain have been carried out within the granite, but our own experience and that of J. H. Allaart (personal communication, 1972) suggests a general horizontal rather than a vertical elongation of xenoliths within the plane of foliation, consistent with that observed in the highly deformed rocks of the Kobberminebugt area.

(3) The widespread evidence of one or more phases of remobilization within the body. Individual areas within the pluton frequently show a complex history of granite formation, deformation, intrusion of basic dykes and then later remobilization, potash metasomatism, and intrusion of younger granitic material often under syn-tectonic conditions, the time span over which these various episodes took place is not known since the youngest events (dated around 1800 Ma, Van Breemen, Allaart & Aftalion 1972) have obliterated isotopic evidence of older events in the material so far investigated in detail.

The general character of the Julianehåb granite suggests that it has crystallized from a series of magmas. The origin of these is not known. The basic parts of the body which probably account for 5% of the total outcrop are almost certainly derived from the mantle during the formation of the mobile belt. What proportion of the granitic material represents remobilized older basement gneisses and granites, or remelted Ketilidian supracrustals, or what proportion is new material from the mantle is unknown. There is considerable local evidence that the intrusion of basic material caused remelting of earlier granites. Whether this process is of regional significance is uncertain,

The complexly folded migmatite zone

The area directly south of the Julianehåb granite consists of an amphibolite facies migmatite complex of granitic gneisses, migmatized supracrustal rocks and intrusive granites, diorites and deformed appinitic plugs. Around Tasermiut fiord on the west coast there is a well-preserved succession of pelitic gneisses, impure psammites (thought to contain a major acid volcanogenic component), and an upper unit of basic lavas. There is no certain correlation between these supracrustal rocks and those of the Graenseland–Midternaes areas in the border zone of the mobile belt. Mapping on the east coast (Andrews *et al.* 1971), where the supracrustal succession is almost continuous (apart from the area occupied by the Julianehåb granite), suggested that the main sequences of supracrustal rocks in the southern and eastern parts of the belt may be early cover rocks deposited on an Archaean basement and metamorphosed before the deposition of the Midternaes–Graenseland succession of the border zone north east of Ivigtut.

The rocks in the migmatite zone are polymetamorphic. Cordierite is developed as a regional metamorphic mineral through much of the area. Andalusite and sillimanite are also widespread suggesting moderately low-pressure and high-temperature conditions. Local patches of greenschist facies rocks are preserved near Tasermiut fiord and at the head of Danells fiord. These pass within 5 to 10 km into granulite facies rocks apparently developed fairly early in the local sequence of events (Escher 1966; Dawes 1970), suggesting that steep thermal gradients must have been present during at least part of the metamorphic history of the area.

The main structures in the complex migmatite zone trend approximately ENE. On the east coast a series of nappes is developed, overturned to the north, on the west coast the pattern is more complex and interference patterns are developed. The structural complexity may be partly due to the large number of granitic and intermediate intrusive bodies in the area which have modified earlier structures during their emplacement and which act as more competent masses during later deformation. Two ENE trending belts of steeply dipping rocks similar to the belt from Kobberminebugt are known in the Sârdloq area on the southern boundary of the Julianehåb granite (Windley 1966), and along the length of Akuliaruseq peninsula (Persoz 1968). The structures in these zones of high deformation are complex and have been described in terms of multiple folding rather than, as we would now interpret them, as representing steep shear zones. The published data show that subhorizontal linear structures are a common feature in these belts, and that earlier structures have been rotated to give steeply plunging fold axes within the subvertical planes. Both of these characters are consistent with the belts being essentially zones of horizontal shear movement active at a fairly late stage in the history of the area.

The flat-lying high-grade migmatite complex

The southern tip of Greenland is composed of migmatized semipelitic and impure psammitic gneisses, intruded by subconcordant granodiorite sheets and folded in a very gentle dome with dips rarely exceeding 10°. After the formation of the main structures the area was metamorphosed under essentially static amphibolite facies conditions with the formation of cordierite and sillimanite on a regional scale. Undeformed basic sheets cutting the complex show granulite facies mineralogy interpreted as reflecting their water-poor chemistry (see also Dawes 1968). U/Pb ages on zircons from the migmatites give a concordia age of 1832 Ma (Gulson & Krogh 1972), which we regard as representing the closing of the U/Pb system in zircons on a regional scale at the end of the cordierite–amphibolite metamorphism. The gneisses show no major repetitions of lithological units. There are no marked linear structures and it appears that the X and Y directions in the strain ellipsoid are approximately equal and horizontal. We interpret the formation of the regional flat-lying structure as due to essentially vertical movements in this part of the mobile belt, possibly related to the rise of major igneous bodies beneath the high grade rocks.

The flat-lying structures are disrupted in many places by the intrusion of post-tectonic norites, monzonites and adamellites of the rapakivi granite suite. These form mushroom-shaped bodies with tops of approximately flat-lying sheets concordant with the regional foliation in the migmatites, and subvertical stems commonly elongated in a NNW direction. Individual bodies may outcrop over areas of more than 5000 km^2. Where they are deeply eroded the lower parts of the tops, and the stems of the bodies are seen to be surrounded by zones of steeply dipping rocks in which the original almost horizontal foliation planes of the country rocks have been downwarped beneath the intrusions (Bridgwater, Sutton & Watterson 1972). This downwarping of the country rocks, which can be traced for up to 5 km from the contacts of the intrusions, is regarded as the effect of subsidence round a upward rising igneous body analogous to the formation of rim synclines round rising salt domes. The downwarping is accompanied by an increase in metamorphic grade and gradual loss of structural coherence of original layered units within the gneisses, so that near to the contact of the intrusions the country rocks commonly develop a new migmatitic structure in which veins of garnet – hypersthene granite surround inclusions of gneisses which have been more resistant to remelting.

Separate intrusions in the rapakivi suite have been dated by Gulson & Krogh between 1774 and 1786 Ma – that is to say the U/Pb systems in the zircons from the granites and norites closed some 50 Ma after that in the regional migmatite complex. We interpret the broad zones of high-grade rocks surrounding the granites as the result of emplacement of very hot basic, intermediate and granitic magmas into country rocks which were still at a high temperature following high-grade metamorphism 50 Ma earlier.

The origin of the magmas from which the rapakivi suite crystallized is debatable. There is a marked concentration of these bodies in areas which had passed through cordierite–amphibolite or cordierite–granulite facies metamorphism, suggesting that there is a close link between the type of igneous body intruded and the metamorphic history immediately before intrusion. Large areas of hypersthene–cordierite–garnet–biotite gneiss developed from the earlier amphibolite facies migmatites, and showing some transitional characters with the granitic parts of the rapakivi granite suite, occur south of Frederiksdal. These gneisses grade from migmatites preserving the original pre-granulite facies structures, to intrusive bodies of garnet–hypersthene granite with potash feldspar megacrysts and containing large inclusions of the earlier gneiss within them where they have moved upwards into less mobilized rock. Whether these bodies should be regarded as possible forerunners to the rapakivi granites or whether they should be regarded as an anatectic suite formed as a result of massive thermal activity in the vicinity of the rapakivi intrusions themselves is not known. It would certainly appear likely that if mantle material is involved in the formation of the rapakivi suite, the chances are very high in this environment for major contamination by crustal material.

Sheets of microcline granite (Escher 1966) and appinitic sills intrude the rapakivi suite and it is possible that some of the appinitic plugs in the Julianehåb granite may post-date the rapakivis to the south. However, in general the rapakivi suite marked the end of plutonic activity within the mobile belt. The regional K/Ar and Rb/Sr mineral ages which group around 1500–1650 Ma suggest that the crust cooled remarkably slowly after the emplacement of the post tectonic granites.

Continuation of the Nagssugtoqidian and Ketilidian mobile belts outside Greenland

The direct relationship between the Nagssugtoqidian and Ketilidian mobile belts is not seen in Greenland. Their easterly extension into Europe is partly obscured by younger rocks and broken up by the Grenville–Dalslandian and Caledonian mobile belts; however, in many respects the Nagssugtoqidian mobile belt shows some strong resemblances to the features developed during the Laxfordian movements in Scotland, while the Ketilidian mobile belt shows strong resemblances to the Sveco-karelian mobile belt of Scandinavia. A direct protion of the Nagssugtoqidian and Ketilidian boundaries in Greenland on a pre-drift model of the Atlantic shows that a possible intersection between the two belts should take place in the Lewisian. It is possible that the complex sequence of events in the Precambrian of north-west Scotland may be due to a Nagssugtoqidian type of deformation modified by superimposed thermal activity of Ketilidian type.

In Labrador the boundary between unreworked Archaean rocks forming the coastal strip and the rocks strongly affected by Proterozoic deformation (Taylor 1969) which occur to the west, must represent the continuation of the Nagssugtoqidian boundary into Canada. The boundary in Labrador strikes apparently NNW to SSE, that is approximately parallel to the main direction of tectonic transport suggested in Greenland. It separates two distinct lithological sequences, the unreworked Archaean rocks to the east being a clear continuation of the old block of west Greenland while the rocks to the west of the boundary, which give Hudsonian or younger K/Ar ages and which consist of high-grade supracrustal rocks, can either be interpreted as Proterozoic sediments and volcanics or as another group of Archaean supracrustal rocks reworked by Hudsonian tectonism. The boundary between the two blocks must represent a zone of very considerable movement. The rocks to the west show a very strong fabric over a large area, with the local development of mylonites and the regional development of rocks with leaf quartz and garnet resembling the Saxony granulites. These trend as a broad belt parallel to the contact with the old gneisses. We have no information about the main direction of tectonic transport involved in the formation of this major feature. However, it seems unlikely that a steeply dipping structure of this size should be formed by vertical shear displacement. As it appears to us that the type of deformation seen is more consistent with a shear movement than with an irrotational compression, we suggest that the mylonite and granulite zone represents a transcurrent displacement between two adjacent blocks. We regard the boundary exposed in Labrador to represent the side margin of a moving block, while the Nagssugtoqidian boundary exposed in Greenland represents the leading edge. It would be of considerable interest to compare palaeomagnetic data from the Archaean rocks of the Superior province with any which could be obtained from the Archaean of eastern Labrador.

Traced southwards the boundary between the Archaean rocks and the rocks involved in Hudsonian tectonism is effectively destroyed by the massive injection of post-tectonic anorthosites, quartz monzonites and adamellites emplaced into the area between 1300 and 1800 Ma ago. In the Makkovik area at the southern end of the Archaean block the Archaean Hopedale gneisses are seen to be overlain by a Proterozoic series of supracrustal rocks (Gandhi, Grasty & Grieve 1969). These include basic volcanic rocks and a major sequence of psammites with clear remnants of acid volcanic material closely resembling the Ketilidian sequences of Kap Farvel and the east coast (Clark 1971; Bridgwater 1970). Metamorphism increases away from the contact and reaches amphibolite facies with the formation of hornblende, biotite, garnet, staurolite and andalusite suggesting conditions similar to those reached in the border zones of the Ketilidian mobile belt. The area was invaded by a series of pre-tectonic, syntectonic and post-tectonic granites and basic rocks, including synkinematic dykes and net-veined bodies, which show close resemblances to the granites and appinite suites of the Julianehåb area – a feature already noted by Kranck in 1939. The area is structurally complex, deformation occurring at different times in belts parallel to the NNE trending contact between the basement and cover. Studies of the deformation in part of the area suggest that crustal shortening of up to 50 % took place during the formation of the main phase of recumbent folds which are overturned towards the basement contact. The magmatic, metamorphic and perhaps to a slightly lesser extent the structural events in the Makkovik area show close resemblances to those recorded from the marginal area of the Ketilidian mobile belt, and we regard the junction between the Archaean block and the younger rocks to be a direct continuation of the Ketilidian boundary zone.

Comparison between the Nagssugtoqidian and Ketilidian mobile belts

From the descriptions given in the preceding sections it can be seen that we regard the Nagssugtoqidian mobile belt as an area dominated by high-pressure conditions and relatively low thermal activity, while the Ketilidian is dominated by high thermal activity and low to medium pressure. It is important to note that these properties are not absolute – we have no direct evidence that tectonic activity in the Ketilidian mobile belt did not lead to crustal shortening on the same scale as that suggested for the Nagssugtoqidian; all we can say is that if this is the case then its effects have largely been masked by the very high thermal activity in the same area.

We suggest that the Nagssugtoqidian mobile belt can be regarded as an area in which considerable subhorizontal movement of crustal material took place at a high angle to the border of the mobile belt, resulting in a piling up of crustal material which in turn gave rise to high-pressure conditions. This piling up of material apparently took place either with little thermal activity or at least such a rate that heat could not be transfered quickly enough through the crustal pile to have an important effect on the type of metamorphism. It is only in the final stages of the formation of the mobile belt that thermal activity becomes at all marked with the formation of the calc alkaline igneous suites in the Angmagssalik area and the recrystallization of kyanite to sillimanite. Evidence of magmatic activity in the early stages of the development of the mobile belt is confined to the restricted occurrences of basic volcanic rocks near the southern boundary, and in the large numbers of basic dykes the emplacement of which was apparently controlled by the same major tectonic régime which controlled the post-dyke deformation. The dykes can be regarded as derived from the mantle, perhaps guided by fractures developed during flexuring of the basement during the first stages of deformation. In the initial stages of the formation of the mobile belt deformation was concentrated in well-defined shear zones and thrusts, suggesting either development in rigid rocks or a relatively rapid build up of stress. Once initiated these shear belts remained zones of structural weakness and resulted in the pattern of undeformed and deformed areas shown in figure 2.

In contrast to the Nagssugtoqidian the Ketilidian mobile belt is dominated throughout its history by magmatic activity and thermal metamorphism. If crustal thickening of the type seen in the Nagssugtoqidian occurred then the relative rate of heat transfer through the pile must have been considerably greater so that the metamorphic assemblages are dominated by cordierite and andalusite-sillimanite rather than kyanite.

Magmatism in the initial stages of the mobile belt was not confined to the intrusion of basic dykes and lavas as is the case in the Nagssugtoqidian but also included regional sequences of acid volcanic rock or sediments with a high proportion of tuffaceous material in them. The later history of the fold belt was dominated by the intrusion of very large amounts of granitic material possibly capped originally by andesitic and acidic lavas. Basic rocks represented by norites, hypersthene diorites and several generations of appinitic rocks form one of the most characteristic suites in the mobile belt. No major areas of unmodified Archaean basement occur in the mobile belt south of the border zone. If any of the granitic gneisses within the mobile belt do represent Archaean basement rocks then they have been so modified by partial remelting during Ketilidian thermal activity that their original characters have been almost completely destroyed. The regional effects of the metamorphism and magmatic activity around 1800 Ma appears to have been so strong that no conclusive isotopic evidence has so far been obtained either for the presence of Archaean rocks within the mobile belt, or for the age of the earliest magmatic events in the mobile belt.

Metamorphism within the belt resembles contact facies developed on a regional scale. Changes in metamorphic facies are commonly abrupt. The major tectonic displacements associated with the formation of the Ketilidian mobile belt are much less easily defined than those suggested for the Nagssugtoqidian belt. Subhorizontal movements normal to the boundary resulting in crustal shortening, and presumably some crustal thickening, apparently took place in the Ivigtut marginal zone although the evidence is much less dramatic than that seen in the Nagssugtoqidian marginal zone. The style of the structures associated with the movements in the border zone differs markedly from that seen in the Nagssugtoqidian, the whole mass of rocks including basement, cover, and early granites, has been bodily rotated rather than displaced along sharply defined shear belts. This may suggest either that at the time deformation took place in the border zone of the Ketilidian both basement and cover had become relatively ductile or that the rate and amount of deformation was much less than that seen on the borders of the Nagssugtoqidian. There is no data regarding the amount of crustal thickening involved – our main argument that it has not been great is based on the metamorphic mineral assemblages where thermal effects have been relatively more important than pressure effects. South of the border zone the evidence for horizontal movements normal to the boundary are less convincing and we suggest that the dominant movements, at least in the younger stages of the history of the mobile belt, have been a mixture of vertical movements associated with the rise of large quantities of igneous material and horizontal movements parallel to the border of the belt resulting in the formation of transcurrent shear belts.

In many respects the two types of mobile belt described resemble the two types of Phanerozoic fold belt discussed by Zwart (1967), with the Nagssugtoqidian showing similarities to the Alpine and the Ketilidian showing similarities to the Hercynian types of belt. The ductile overthrusting and crustal shortening which characterize the Nagssugtoqidian mobile belt are consistent with the deformation expected in the marginal part of a continental plate in collision contact with another continental block. The Nagssugtoqidian displacements, whether expressed in plate tectonic terms or not, are of the type expected at rather deeper levels than are now exposed in the Alps and at the NW front of the Caledonian. In contrast to the situation described from the Alps however, little or no ocean floor material appears to have been trapped by the crustal movements which resulted in formation of the Nagssugtoqidian.

The complex movements associated with the formation of the Ketilidian make it difficult to find a more recent analogue for comparison. The type of igneous activity in the area is remarkably close to that of the Andean chain, where major vertical displacements have been described. As the relationship between the Andean vertical displacements and the adjacent plate margin is still problematical (Pitcher & Cobbing 1972), a plate tectonic interpretation of the Ketilidian is correspondingly difficult. It is possible that in both areas the vertical displacements are secondary effects of the mass displacement of igneous material rather than a direct reflexion of the relative movements along plate margins. Whether one should regard the massive thermal activity in south Greenland as the result of the movement of plates or whether one should perhaps regard the thermal activity as a possible mechanism by which the movement of plates was effected is debatable. Certainly the persistence of igneous activity in the area for 1000 to 1500 Ma suggests a fundamental source of heat in the mantle, which may have been available during a variety of major tectonic régimes.

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