GRØNLANDS GEOLOGISKE UNDERSØGELSE
BULLETIN No. 26

STRUCTURAL ANALYSIS OF A FAULT IN SOUTH-WEST GREENLAND

BY

NIELS HENRIKSEN

WITH 11 FIGURES IN THE TEXT AND 1 MAP

Reprinted from
Meddelelser om Grønland, Bd. 162, Nr. 9

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BIANCO LUNOS BOGTRYKKERI A/S
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CONTENTS

Abstract.

Detailed analysis has shown the step-wise development of a WNW-ESE trending wrench fault, the Laksenæs fault, in the Ivigtut area of SW Greenland. The fault has a total horizontal displacement of 6 km, with sinistral movement, and a vertical displacement of approximately 2 km.

The horizontal displacement can be shown to have taken place in three successive stages, each of which occurred in a different geological period. The first horizontal displacement of 1.5 km took place in the Ketilidian and/or early Kuánitic periods and was followed by a displacement of 1.5 km in the Sanerutian period and 3 km in the Gardar period. Vertical displacement took place only with the first two stages of horizontal displacement.

The Laksenæs fault is cut by a system of NNW trending dykes which have been provisionally ascribed to the Tertiary.

Introduction.

During the mapping by G. G. U.[1]) of the Ivigtut area, SW Greenland, Mr. C. H. Emeleus showed that a large fault cuts the Grønnedal Nepheline-syenite—he called this the Laksenæs fault. The fault continues for a long distance to the west of Grønnedal in the area which was mapped by the writer in the summers of 1956 and 1957. There are many similar faults in the Ivigtut area and as it was decided to make a detailed investigation of one of them, the writer carried out, in 1958, more detailed mapping of the Laksenæs fault within the area which he had mapped in 1956 and 1957.

The mapping of the Ivigtut area was carried out under the leadership of Mr. A. Berthelsen. In 1956 and 1958 I was assisted during the field work by Mr. B. Kraul Jensen and in 1957 by Mr. Simon Lægaard.

I wish to thank the board of G. G. U. for the opportunity to take part in the mapping of the Ivigtut area, and professor A. Noe-Nygaard for the working facilities afforded me in the Mineralogical Museum of

[1]) Grønlands Geologiske Undersøgelse (G.G.U.) = Geological Survey of Greenland.

the University of Copenhagen. Sincere thanks are due to Mr. BERTHELSEN for introducing me to the problems of structural geology and for supervising my work. I also wish to thank Mr. J. WATTERSON for assistance with the translation of this paper and both he and Mr. E. BONDESEN for their suggestions and discussions. For good companionship during the field work I wish to thank all who took part in the work of G. G. U. around Ivigtut and especially my assistants B. KRAUL JENSEN and S. LÆGAARD.

The geology of the area surrounding the fault.

The fault is found to the north of Ivigtut and in the investigated area, between Arsuk Fjord in the east and Kuánit fjord in the west, trends N. 70 W. and is vertical. East of Arsuk Fjord it can be traced in the same direction almost to the inland ice and continues to the west of the area mapped, along Kuánit fjord and between the islands of Tôrnârssuk and Sermersût. Only minor horizontal displacements up to a little less than 1 km, are found on the fault to the east of Arsuk Fjord. To the west of the area mapped it has not been possible to measure the displacement along the fault as here it is thought to follow the Kuánit fjord: this is confirmed by the pattern of fold axes on Sermersût and Tôrnârssuk and by the occurrence of a fault on the southernmost peninsula of Tôrnârssuk which is on the continuation of the line of the Laksenæs fault.

The investigated section of the fault is 16—17 km long and the total displacement can be shown to be made up of three partial displacements, each of which occurred in a different geological period. The total horizontal displacement is 6 km with sinistral movement, and the vertical displacement is approximately 2 km.

In the area investigated the following chronology, which is similar to that found in neighbouring areas, has been established.

Post Gardar period
Gardar period
Sanerutian period
Kuánitic period
Ketilidian period

Ketilidian period: This is represented by folded migmatitic gneisses which, in the area mapped in detail, can be separated into two series viz. the Gabbro Anorthosite series and the Sermersût series. In both these series two different fold axes are found, one of which has an approximately E—W trend and plunges at low angles to the east, while the other has a NNE trend and plunges steeply to either north or south. The NNE axis is weakly developed and only seldom seen; the relative age of the axes is not known.

The Gabbro Anorthosite series is made up of granodioritic and quartz-dioritic gneisses which contain many bands, boudins, and lens shaped inclusions of anorthositic and gabbro anorthositic rock. This series also contains bands of amphibolite and ultrabasic lenses. The Sermersût series is also made up of granodioritic and quartz-dioritic gneisses but with mica-schist horizons and layers of amphibolite. Both of the gneiss series are cut by Ketilidian pegmatites and therefore have a migmatitic appearance. Both series were recrystallised under amphibolite facies conditions during the Ketilidian folding.

A Ketilidian antiform structure has been used in the evaluation of the displacement of the Ketilidian rocks by the Laksenæs fault. On the north side of the fault the hinge of this antiform is seen south of Kuánit fjord where the trace of the axial plane forms a bend which is concave towards the south, and is cut by the fault between lake 355 and Christians Havn Sø. The trace of the axial plane to the south of the fault is intersected by the latter just to the west of Arsuk fjord. North of the fault, the boundary between the Gabbro Anorthosite series and the Sermersût series is found in the hinge zone of the antiform, but south of the fault the boundary is seen west of Christians Havn Sø where it is in the southern limb of the antiform.

The Kuánitic period is marked by the intrusion of basic dykes which, on the basis of their different trends, can be separated into three different sets. The directions of these sets are NE—ENE, NNW, and WNW but owing to the small number of intersections found it has not been possible to establish the relative ages of the three sets with any certainty. The WNW set is probably the youngest. In neighbouring areas the NNW set is the oldest, and the WNW set the youngest of the Kuánitic dykes.

In Sanerutian time all the rocks described above were subjected to regional metamorphism and weak folding but traces of the folding are found only in the extreme SE part of the area investigated. The metamorphic degree corresponds to epidote-amphibolite facies in the western part of the area and becomes higher towards the east with amphibolite facies in the area around Arsuk fjord. Thus, in Sanerutian time the gneisses in the west underwent retrogressive metamorphism from amphibolite to epidote-amphibolite facies and at the same time Kuánitic dykes were changed to amphibolites.

The Gardar period is represented by numerous dykes which include lamprophyres, granophyres, dolerites, and trachytes, emplaced in that order. The only dykes which can be correlated across the fault are the dolerites of which there are three generations, the first of which trends 75—90E, the second 45—70E and the last 30—50E.

Fig. 1. View along the eastern part of the fault, looking eastwards, with Christians Havn Sø in the foreground. Note the difference in the level of the ground on either side of the fault.

The Ketilidian, Kuánitic, Sanerutian, and Gardar periods are all considered to be pre-Cambrian.

More dolerite dykes were intruded in post Gardar time; these form a swarm trending N10—30W, parallel to the coast, and all dip 70—80W.

Description of the fault.

Between Arsuk Fjord and Kuánit fjord the fault is easily recognised because of the large crush zone which occurs along it and often there is also a well defined gully developed, or a scarp separating the northern side of the fault from the higher southern side (see fig. 1).

The Laksenæs fault has an almost straight WNW trend and the plane of the fault is vertical or nearly so. Although it cannot be seen directly because of the wide crush zone, the vertical character is shown by the almost straight course of the fault in an area of high relief. South-east from the head of Kuánit fjord the fault splits up into two separate faults 300—400 m apart. The southern branch has the smaller displacement and can be regarded as an offshoot of the larger fault zone. Further to the east the southern branch thins out and joins up with a NNE fault on which there has been only a small horizontal displacement—200 m on a Kuánitic dyke.Further to the west the displacement on the southern branch is 0.5—1.5 km on Kuánitic dykes so it can be seen that it becomes less important towards the east. There is no difference

Fig. 2. Crush zone along the southern branch of the fault, south of Kuánit fjord. The dyke which can be seen just beyond the third snow patch is number 1 on the map. The scale is given by the man in the foreground, right of centre.

in appearance between the two branches of the fault and sometimes the southern branch has the wider crush zone and gives the impression of being the more important of the two (see fig. 2).

The widths of the crush zones surrounding the faults are from 10—50 m and the positions of the fault planes therefore cannot be accurrately determined. As the movement has undoubtedly not been confined to one plane, it is more correct to describe it as taking place within a zone which is probably a little narrower than the crush zone.

Besides the crushing down which has been mentioned the rocks often have a red coloration, best seen in large pegmatites in the gneiss, which can be found as far as 200 m from the fault, but normally only within and close to the movement zone. The coloration is less well developed in the gneiss than in the pegmatites, and it is seldom seen in the Kuánitic and Gardar dykes.

The fault zone is also marked by the formation of chlorite and epidote within it: the chlorite is especially common on movement surfaces on

Fig. 3. Breccia from the central part of the fault zone, between Christians Havn Sø and Arsuk Fjord. The white spots are leucocratic inclusions enclosed by the dark, mainly chloritic, matrix.

which it forms a complete coating. There is also a chloritisation of the basic dykes, especially Kuánitic dykes, where they are found in the movement zones. Epidote is found as a fissure filling and commonly forms good crystals in cavities where it is associated with quartz. Quartz itself occurs as a normal fissure filling material, as also does calcite. The veins, which are 2—3 mm wide, can be very regular in both size and direction so that a network of veins is seen on rock surfaces. The different kinds of fissures and cracks are found throughout the length of the fault.

The features of the Laksenæs fault which have been described are also characteristic for the smaller faults which occur in the area mapped, but breccias are found only along the Laksenæs fault. The breccia zones occur only in the central parts of the movement zone and are narrow and elongated parallel to the direction of the fault. The inclusions in the breccia are quite small, up to three or four cm long, and surrounded by a chloritic matrix. In most cases the breccias seem to be formed in the places where the fault movements have affected Kuánitic dykes from which the chloritic matrix has been produced. The angular inclusions consist of leucocratic material which is thought to be formed from the gneisses (see fig. 3). Along the investigated part of the fault

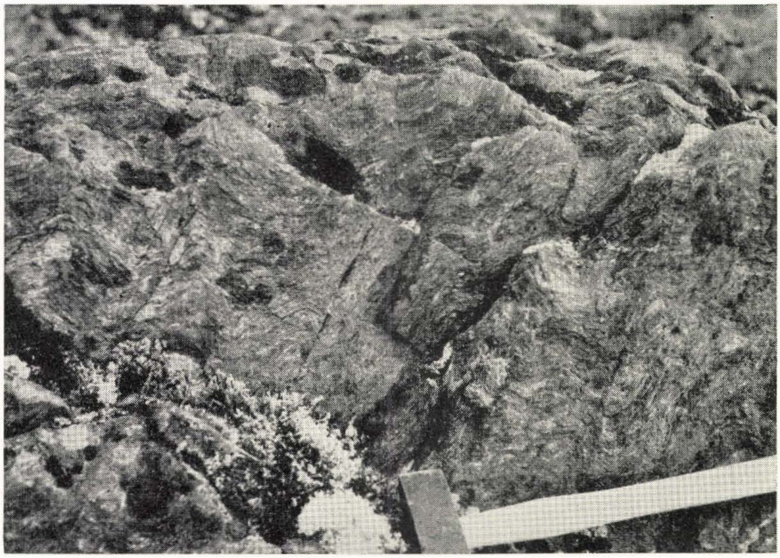

Fig. 4. Shear folds, produced by the fault movements, in a Kuánitic dyke west of Christians Havn Sø.

there are about six or seven of the breccias which can each be traced for about 10 m except for one which has been followed for 30 or 40 m.

Other features concerned with the movement on the fault are 1/ folding, and 2/ a coarse plasto-mylonitisation of some of the rocks. Along the whole length of the fault remnants of basic dykes are found in the movement zone. These pieces of Kuánitic dykes cannot be linked with the continuous dykes outside the movement zone and are often strongly sheared and sometimes folded. As the folds have not been found outside the movement zones they must have been formed by the fault movements and can therefore be regarded as shear folds. During the Sanerutian period a linear structure was developed within the dykes, parallel to their margins, and it is this structure which has been folded by the fault movements; the shear folds must therefore have been formed later than the Sanerutian period. The folds are always small with an amplitude of 5—10 cm (see fig. 4).

The plasto-mylonitisation, which in some places is so intense that no original features of the rock can be recognised, is the result of plastic deformation and shearing of the rock with the formation of irregular dark schlieren in the fault zone. These schlieren are often formed from Kuánitic dykes and have a characteristic brown colour on weathered surfaces. The effect of the shearing is not strong enough to form banded rocks and the irregularity of individual schlieren has resulted in an homogenisation rather than the formation of a linear structure. The type of deformation which has just been described is found mainly in the western part of the area where only little crushing of the rocks has been seen, and so it is assumed that this deformation is of a wholly plastic nature. It has been said that the homogenisation is found only within the fault zone but slight traces of it are seen also in the surrounding rocks.

Microscopical description of some rocks affected by the fault movements.

Investigation of the gneisses and Kuánitic dykes is made difficult by the problem of distinguishing between changes due to the second regional metamorphism, and the changes produced by the fault movement. In addition to a marked chloritisation, the fault movements have caused the formation of many micro-faults and sometimes a recrystallisation of quartz and plagioclase in cracks and fissures. Sericitisation of the plagioclase has been seen in many of the rocks examined but it cannot be definitely ascribed to the fault movements because a similar alteration is seen in some of the rocks from outside the fault zone. It is mainly the dark minerals which have been altered and on only a few occasions have the light minerals been recrystallised along small planes of movement; the dark minerals which have been altered to chlorite are hornblende, augite, and biotite, while the epidote appears to have been preserved, although it is possible that there has been some formation of new epidote as the matrix of one of the breccias examined consists of epidote together with chlorite. In other breccias the matrix consists only of chlorite—penninite and another chlorite mineral.

The rocks described below are some of those in which alterations have been produced as a result of the fault movements.

Specimen 19769. Leucocratic gneiss.

This specimen is taken from the centre of the fault zone which, in this locality —east of Christians Havn Sø, has the character of a wide crush zone in which the pegmatites are coloured red.

The texture is hetero-granoblastic with a grain size of 0.2—0.5 mm and single larger grains, up to 2 mm, are set in the finer grained groundmass. Quartz and felspar, which together make up 95$^0/_0$ of the rock, show a weak shape orientation and the remainder of the rock is made up of chlorite, penninite, muscovite, and an epidote mineral.

The plagioclase, which seldom shows twinning, has a refractive index somewhat lower than that of quartz and a little higher than that of balsam, which shows it to be a calcium-poor oligoclase; it is only slightly serictised. Both the quartzes in the groundmass and the larger individuals, are elongated; they also have undulatory extinction and can be optically bi-axial.

Penninite and the other chlorite mineral are found as small stumpy crystals which are aligned roughly parallel to the elongation of the quartz grains, and because of their habit are thought to be secondary after biotite which is not found in the section. Single scattered grains of epidote or clinozoisite are present and also a small amount of interstitial microcline, some of which is perthitic and replacing plagioclase.

The cataclastic nature of the deformation is shown by a number of micro-faults of which there are the two following types: 1. broad zones with gently irregular trends which are determined by the pre-existing texture. 2. small cross-cutting offsets which are more straight and regular than the first type.

1. These are characterised by the recrystallisation of quartz and plagioclase within and along the borders of the movement zones. This is mostly in situ recrystallisation but newly formed plagioclase grains are found within the zones where

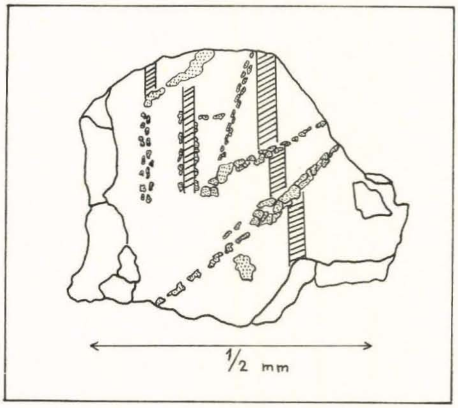

Fig. 5. Sketch from a thin section of a cataclastic gneiss, showing blasto-cataclastic seams and micro-faults in a plagioclase crystal. The specimen is from the central part of the fault zone east of Christians Havn Sø.

these cut through large individual quartz crystals; similarly, quartz is found in the movement zones where these cut through plagioclase crystals so there must have been some transport of material along the fissures. In one of the wider movement zones of this type a distinct micro-breccia has been found.

2. These micro-faults consist of thin blasto-cataclastic seams which cut individual mineral grains and which are both less distinct and less persistent than the first type. A recrystallisation and formation of new plagioclase has taken place along these seams and the new plagioclase has a lower refractive index than the plagioclase which surrounds it (see fig. 5). The plagioclase with the low refractive index is also found in the seams where they cut through quartz grains.

A few epidote veins are seen which appear to be later than the two types of micro-faults described above.

The mineral lineation is perpendicular to the cataclastic movements and must have been formed before they took place, possibly during the second regional metamorphism. There were also some movements at a small angle to the main cataclastic movement direction and so the whole can be spoken of as a differentiated system of movements.

Specimen 39222. Cataclastic gneiss.

This was taken from a locality where the rocks have been stained red and chloritised. In a vesicular rock, similar to this specimen, calcite was found filling the vesicles and also filling irregular cracks.

In thin section the rock is homogeneous and granoblastic with the grain size of the plagioclase up to 0.7 mm, while grains of the other minerals are seldom larger than 0.3 mm. The rock consists of 75—80 % plagioclase, with about 10 % calcite, 5—8 % chlorite, and 3—4 % epidote, together with small amounts of muscovite and apatite. From its mineral composition the rock appears to have been originally a Gabbro Anorthosite.

Plagioclase occurs as relict crystals and as smaller recrystallised grains: the two distinct types are thought to be the results of the two regional metamorphisms and have nothing to do with the later cataclastic deformation. The twin planes of the first generation plagioclase, which have been obscured by alteration, are cut across by small movements and in some cases slightly bent: the composition of this plagioclase is about An 23. Most of the plagioclase is recrystallised and belongs to the second generation in which twinning is rare: it is eu-granoblastic and the grain boundaries are weakly lobate. The plagioclase of both generations is somewhat sericitised and contains small grains of clinozoisite. The clinozoisite was formed because the former composition of the plagioclase was not stable during the second metamorphism.

The shapes of the large calcite crystals are determined by the surrounding small plagioclase grains which differ from the other plagioclases in not being sericitised. Although no direct evidence is available the calcite is thought to have been introduced into the rock during the fault movements.

Penninite and another chlorite mineral together with larger grains of epidote occur in aggregates which have the same form as aggregates of biotite and epidote which are found in the non-cataclastic rocks. It seems likely therefore, that the chlorite has been formed from the biotite although there are no relics of biotite seen in the thin section.

The red colour of the rock is due to staining of the plagioclase but the cause of this cannot be seen in thin section.

Specimen 39237. Breccia rock.

The specimen, which is taken from the centre of the fault zone, contains angular leucocratic inclusions up to 2 cm in size, which make up half the rock. Single grains are often cut by thin veins of matrix material. Field observations have shown that the matrix material is probably derived from a sheared Kuánitic dyke. The breccia is also cut by a few thin quartz veins.

In thin section four stages in the development of the dyke can be recognised. The first and second are due to the first and second metamorphisms, while the third and fourth stages are due to the later cataclastic deformation. The first two stages can be seen only in the gneiss inclusions. Part of this rock is shown in fig. 6 in which the numbers correspond to the four stages described below.

Stage 1: Except in one case, this is seen only in the larger relict plagioclase crystals which are 3—4 mm in size and partly recrystallised into smaller rounded plagioclase grains. In neither of the two types of plagioclase has the composition been determined accurately because of the rarity of twinned crystals, but as the refractive index of both plagioclases is somewhat lower than that of quartz, they are probably olioclase. Apart from the plagioclases, large aggregates of quartz are also found in the inclusions and these are thought to have been originally single large quartz grains which were granulated and recrystallised during the second stage.

Stage 2: In this the larger individuals of quartz and plagioclase were recrystallised and when the recrystallised grains are found in the bigger inclusions, the texture is eu-granoblastic. The original plagioclase crystals are surrounded by recrystallised material of the same composition which forms rims with a mortar structure, probably formed during the second stage. The quartz aggregates, mentioned previously, are made up of a row of individual grains which have a linear orientation showing that the recrystallisation took place while the rock was under stress. In the smaller inclusions there is now no trace of the original crystals and the grain size of the recrystallised minerals is smaller than in the larger inclusions: this may be due to the stronger cataclastic deformation of the smaller inclusions. In both the primary and secondary plagioclase are found some small crystals of muscovite

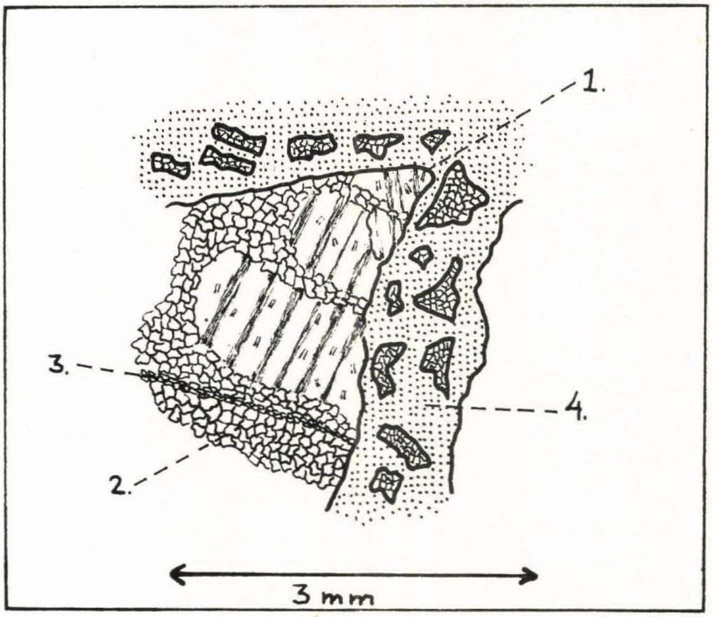

Fig. 6. Sketch from a thin section of a rock brecciated by the fault movements. The numbers refer to the four stages of development described in the text. The specimen is from the central part of the fault zone west of lake 355.

and a chlorite mineral in addition to a few larger flakes of penninite. It is possible that the chlorites were formed from biotite during the third stage but they are certainly cut by structures of the fourth stage.

Stage 3: Fine grained seams of recrystallised plagioclase cutting the earlier plagioclases are formed during this stage and probably also some new small flakes of chlorite.

Stage 4: The brecciation took place during this stage. The light green matrix is an aggregate of fine grained chlorite which has anomalous blue and brownish polarisation colours, with some small grains of an epidote mineral, and titanite(?).

Specimen 39228. Cataclastic Kuánitic dyke.

The specimen is taken from the margin of the southern fault zone where the rock surface is traversed by a network of narrow quartz veins. There is a transition zone between the dyke, and the surrounding gneiss in which schlieren of both rock types are found.

The rock is formed mainly of plagioclase crystals, about 0.1 mm in size, and flakes of penninite about 0.5 mm in length. There are also small amounts of ore, titanite, leucoxene, and muscovite, and some cross cutting quartz veins are found.

The plagioclase has been recrystallised to a hemi-granoblastic aggregate in which the individual grains have weakly lobate borders. As twinned crystals are uncommon the composition of the felspar has not been accurately determined but the refractive index is a little lower than that of quartz and corresponds to that of a calcic oligoclase. The plagioclase crystals are cut by chlorite grains which are also found in large irregular aggregates which are characterised by a uniform orientation of the chlorites over small areas, but which do not have a uniform orientation throughout the rock. The chlorite contains inclusions of small irregular grains of titanite which also form rims round the evenly distributed ore grains which are often altered to leucoxene.

The rock described above is cut by a network of quartz veins which are up to 2 mm wide and in which the individual crystals are up to 1 mm in size but are more usually 0.2—0.5 mm.

In the area from which this specimen was taken, the plagioclase in the Kuánitic dykes is usually found in completely recrystallised aggregates. It is likely therefore, that the only effects of the cataclastic deformation on the specimen described, are the chloritisation of hornblende and the formation of quartz veins. It is possible however that the alteration of the ore grains to leucoxene also took place at this time and the possibility of the light minerals being affected by the cataclasis cannot be excluded. The crushing down of the originally larger plagioclases may also have taken place at this stage.

Specimen 39253. Altered dolerite.

This specimen is taken from the central part of the fault zone and is coarse grained and ophitic, containing plagioclase crystals 2—3 mm in size and pseudomorphs after augite which are 1.0—1.5 mm across. The following minerals are found in addition to the plagioclase — calcite, penninite (pseudomorphic after augite), titanite, ore, leucoxene, sericite, and accessory apatite which occurs in rather large crystals.

The plagioclase is strongly sericitised and occasionally contains small penninite flakes, as well as quite large amounts of calcite and small indeterminable grains of a mineral with high relief and high birefringence. The strong alteration of the plagioclase prevented determination of its composition.

All the augite has been replaced by penninite which forms well developed pseudomorphs and contains small inclusions of titanite and, less commonly, small aggregates of calcite. The ore grains are often surrounded by a rim of leucoxene and because of their skeleton like form are thought to be, in many cases, ilmenite.

Fractures in the rock are filled with calcite and a felspar which has a refractive index close to that of balsam and is therefore probably albitic.

It is remarkable that no trace of a mechanical crushing down can be seen in this rock.

The development of the Laksenæs fault.

A. The displacement of the Ketilidian gneisses.

This involves the calculation of 1/ the horizontal component, and 2/ the vertical component.

1. *The horizontal component.*

To calculate this it has been necessary to make transverse profile constructions by the Wegmann method, for which the fold axes have been determined only by plotting planar structures on a Wulff net.

By means of the profile constructions it have been possible to show that the axial plane of the antiform structure, which is cut at a small angle by the fault, dips to the north on the northern side of the fault and dips to the south on the southern side. Therefore, it can be assumed that the part of the axial plane which cannot be constructed, is vertical or nearly so. Because of this, the horizontal displacement on the fault can be taken as the horizontal distance between the two places at which the axial plane is intersected by the fault. The calculation shows a sinistral displacement of 6 km i. e. the relative movement of the southern block has been to the east.

2. *The vertical component.*

The calculation of this is much more difficult and has been carried out by three different methods which give somewhat varying results.

a. Calculation of the vertical component using the boundary between the Gabbro Anorthosite series and the Sermersût series as a datum plane.

The geological sketch map shows that in the southern part of the hinge zone of the antiform, south of Kuánit fjord, the boundary between the two gneiss series is bent round as it approaches the fault. No corresponding structure is seen on the southern side of the fault where the boundary between the two series continues its straight E—W course right up to the fault. The fact that the fold axes just to the north of the fault are steeper than those elsewhere (see fig. 7) shows that the deflection of the boundary on this side of the fault is caused by drag along the fault. Relative upward and eastward movement of the southern block would cause a steepening of the layers on the northern side of the fault resulting in the steepening of the fold axes which has been observed.

From the foregoing it can be assumed that a certain amount of drag has taken place on the northern side of the fault, and therefore the boundary between the gneisses must have followed a different course before the movements on the fault took place. The course of the boundary between the hinge zone and the fault would

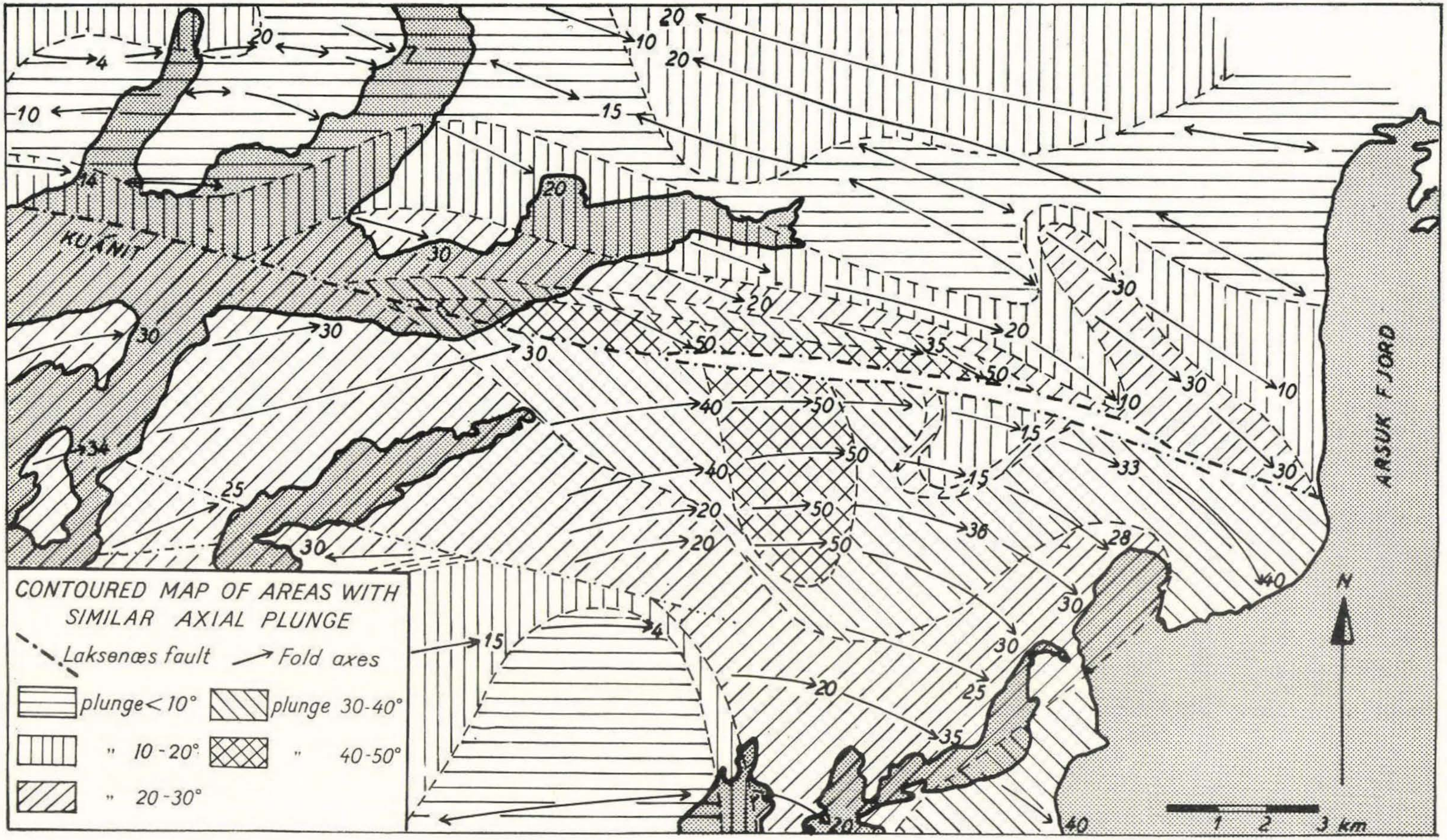

Fig. 7. For explanation see text page 33.

have been more straight and would have been intersected by the fault further to the west, if no drag had taken place. The point at which the boundary would have been intersected by the fault if no drag had taken place, can be found by extrapolating the course of the boundary from where it runs in a straight line to where this straight line would be intersected by the fault. This point is found to be 500 m further to the west than the actual intersection. As the fold axes now have

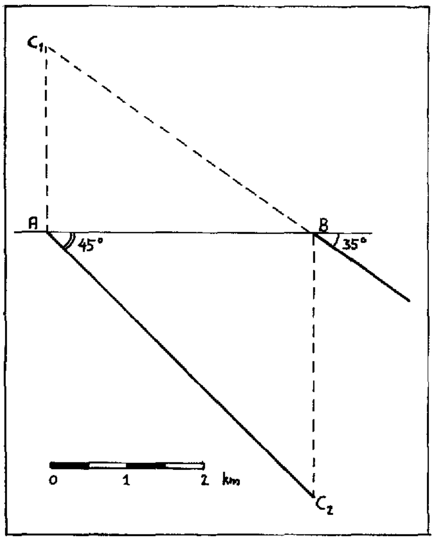

Fig. 8. Diagram showing the vertical displacement of the boundary between the two gneiss series. Heavy lines show the trace of the boundary surface on the fault plane. AC_2: trace of the northern boundary surface. C_1B: direction of trace of the southern boundary surface. AB: horizontal distance between the two boundary surfaces = 3.5 km.

a constant trend in the region of the hinge zone of the antiform, it can be assumed that the attitude of the gneiss boundaries before the drag took place, was the same as is now found just to the south of the antiform closure.

We now have two planes by which the displacement on the fault can be calculated; these are the boundary planes between the two gneiss series, the one on the northern side of the fault, which has been deformed, and the other on the southern side of the fault. The attitudes of the planes can be found from the strike and dip readings in the surrounding gneisses; this will eliminate any errors which may be in the constructions.

The calculations have been carried out in the following way. The line of intersection of each boundary plane with the fault plane is found by means of a Wulff net construction. By these means it has been found that the apparent dip on the vertical fault plane of the boundary plane on the northern side is 45° E, and that of the boundary plane on the southern side is 35° E. The horizontal component has already been calculated and when this is allowed for it is found that the intersections of the two boundary planes with the fault plane are 3.5 km apart. To bring the two boundary planes into alignment it is necessary to have a relative lowering of the southern block and the amount of this vertical movement can be calculated by using the data given above. The method is shown by fig. 8 in which the fault plane lies in the plane of the paper.

We have that $BC_2 = \tan 45° \times 3.5$, hence $BC_2 = 3.5$
$AC_1 = \tan 35° \times 3.5$, hence $AC_1 = 2.5$

The vertical displacement is therefore either 3.5 km or 2.5 km. An intermediate value of 3.0 km is thought to be the most likely as there must be a smooth transition between the apparent dips of the boundaries on the fault plane.

b. Calculation of the vertical displacement using the hinge zone in the antiform.

It can be imagined that in the continuation of the boundary plane on the southern side of the fault, there exists a hypothetical hinge zone corresponding to the real hinge zone on the northern side. It is thought that this imaginary hinge zone would be situated north of the fault plane, north of Christians Havn Sø.

When the horizontal component has been allowed for, the vertical component can be found by calculating how much the hinge zone on the northern side of the fault must be elevated in order to make it close round the same fold axis as the imaginary closure of the boundary to the south of the fault. The fold axis in the hinge zone south of Kuánit fjord plunges 20° E and the axis to the south of the fault at Christians Havn Sø plunges about 35° E. After allowance has been made for the horizontal movement, the distance between the two closures referred to is found to be 3.5 km. The vertical displacement is found by the method shown in fig. 9.

It has been shown that $AC_1 = \tan 35° \times 3.5$, hence $AC_1 = 2.5$
$BC_2 = \tan 20° \times 3.5$, hence $BC_2 = 1.3$

The vertical displacement is therefore either 1.3 km or 2.5 km, with the southern being raised relative to the northern block.

Towards the south-east there is a steepening of the fold axes which is not due to the flexuring of the southern block which is described later. The plunge of the antiformal structure of the gneiss boundaries must therefore become steeper towards the east and the amount of vertical displacement is probably between 1.8 and 2.0 km, the actual value depending on where the steepening of the axis begins.

c. Calculation of the vertical displacement using the variation in the plunge of fold axes in the area surrounding the fault.

Owing to the graphical constructions involved this method is not so accurate as the other two, but it does enable an analysis to be made of the development of the fault.

A map of the area round the Laksenæs fault has been made (fig. 7) in which the constructed fold axes have been used to draw contours

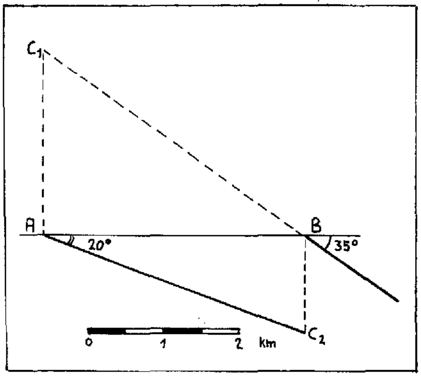

Fig. 9. Diagram showing the vertical displacement of a fold axis in the hinge zone. Heavy lines show axial plunge at the antiformal closure of the folded boundary and at the imaginary closure.
AC_2: axial plunge in the west. C_1B: axial plunge in the east. AB: distance, measured along the axial trace, between the two closures. AC_1 or BC_2: calculated vertical displacement.

enclosing areas in which the axial plunge is more or less constant. The contours show only the larger variations in the plunge as the smaller variations were eliminated in the Wulff net constructions.

Fig. 7 shows that there is a steepening of the fold axes on the south side of the fault which is not found on the northern side where the plunge is fairly constant (0—20°), except in those places where there has been drag along the fault. This difference can be explained by assuming that during the fault movement a buckling of the southern block took place which resulted in the steepening of the fold axes (see fig. 10). This assumption also provides an explanation of the decrease in the displacement towards the east—east of Arsuk Fjord the horizontal displacement the Gardar rocks is only about 1 km.

The fold axes on both sides of the fault are almost parallel and so it is probable that, before the buckling took place, the plunge on the

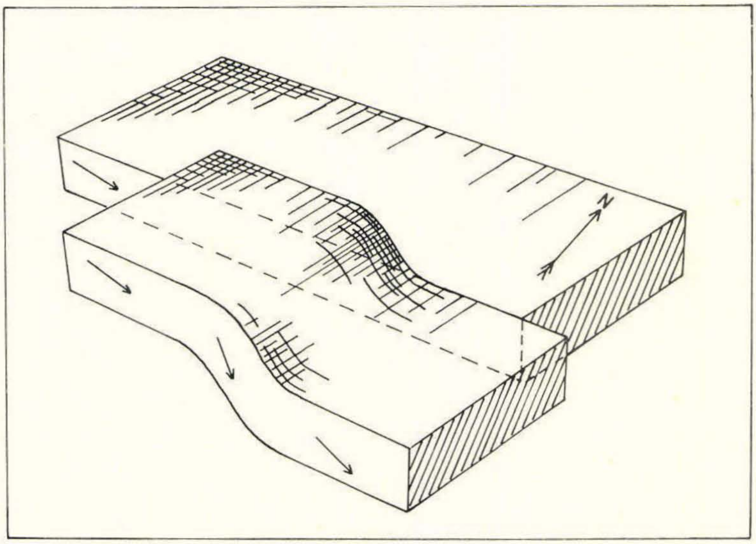

Fig. 10. Sketch showing the relation of the flexured southern block to the undeformed northern block and illustrating the decrease in both vertical and horizontal displacement towards the east. Arrows indicate plunges of the fold axes.

south side of the fault was about 20° E—the same as that on the northern side. If this is so the vertical displacement can be found by projecting along the fold axes corresponding points on both sides of the fault and measuring the vertical distance between them. The projection has been carried out by pure graphical methods which are shown in fig. 11 in which the plane of the paper is thought to correspond to the plane of the fault.

By this method it is estimated that the relative upward movement of the southern block is 3.0 km but this applies only to a 10 km section of the fault. The increasing steepness of the fold axes towards the west suggests that both the horizontal and vertical displacements also increase in this direction.

The conclusion to be drawn from the foregoing calculations is that the horizontal displacement of the Ketilidian gneisses is 6 km and that the movement was sinistral. The amount of vertical displacement is probably best given by method b. as the two parts of the antiform almost certainly would have had a common fold axis. In allowing for the drag in method a., small variations in the corrected dips lead to quite wide differences in the final result which is therefore liable to be inaccurate. In method c. it was necessary to estimate the plunge of the fold axes before the buckling of the southern block took place. This estimate is therefore liable to be inaccurate because there may have originally been a steepening of the fold axes toward the east which has not been

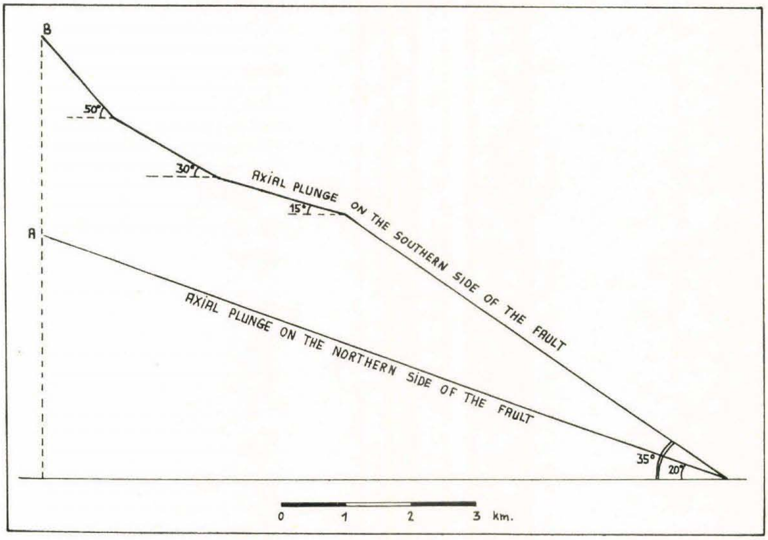

Fig. 11. Axial plunges in corresponding areas on either side of the fault. AB is the vertical distance between upwardly projected corresponding points, which corresponds to the vertical displacement.

allowed for in the calculation, and would mean that the figure obtained for the displacement is too high.

The vertical displacement may therefore be taken as being between 1.8 and 2.0 km with a relative rise of the southern block, in the area south of Kuánit fjord. The difference between these figures and the result obtained by method c. suggests that all the vertical displacement has been caused by buckling of the southern block.

As so many assumptions have been made in the calculation of the vertical displacement, the results obtained should be viewed with caution.

B. Displacement of the Kuánitic dykes.

It has been possible to correlate across the fault only one Kuánitic dyke: this dyke is 30—40 m broad and, unlike other dykes of the same age, contains large felspar phenocrysts which have enabled it to be definitely identified on both sides of the fault. The trend of the dyke is almost parallel to that of the fault and in some places it may have been intruded along the fault plane. Because of this an estimate can be given only of the maximum possible displacement, which is the sum of the displacements along the two parallel faults. The displacement along the northern fault is not more than 3 km and along the southern fault not more than 1.5 km and not less than 500 m; the maximum possible total horizontal displacement is therefore 4.5 km. As the fault plane is vertical only the horizontal displacement can be estimated.

The dyke on which the measurements were made belongs to the youngest generation of Kuánitic dykes and so it is possible that the two earlier generations of Kuánitic dykes have been displaced further, although it has not been possible to correlate any of these across the fault. However a dyke (number 1 on the map) belonging to one of the earlier generations has been found to be displaced 1.5 km along the southern fault—the same distance as the dyke belonging to the youngest generation.

It may seem strange that although there are so many Kuánitic dykes in the area mapped, it has been possible to correlate only one of them across the fault. This is due however, to the uniform rock type of the dykes and to their irregularity which makes it difficult to identify corresponding pieces of the same dyke. It is possible too, that because of the different conditions in the fault zone, some of the dykes did not continue across the fault which, as has been described, was in existence before the intrusions of the dykes.

C. Displacement of Gardar dykes.

Some of the broad dolerite dykes of this period can, almost certainly, be correlated across the fault, unlike the thinner dykes of the same age which can only be mapped as individual pieces. In areas close to the fault, the trends of these pieces are uncertain. The correlated dykes are 10—30 m broad, vertical, and belong to two or three generations; they are displaced by the fault between 2.2 and 3.4 km and all the movement is sinistral.

Near Kuánit fjord, in the western part of the area, a dolerite dyke belonging to the first generation of Gardar dykes (number 2 on the map) has been displaced 3.4 km. In the same area a dyke (number 3 on the map) which probably belongs to the third generation, has been displaced only 2.6 km showing that movement on the fault took place between the times of intrusion of these dykes.

In the central part of the area which has been mapped in detail, a dyke belonging to the first generation (number 4 on the map) is displaced 1.2 km by the southern fault and 2.2 km by the northern fault, making a total displacement of 3.4 km. Because of Quaternary cover the figure given for the southern fault may be inaccurate.

Near Arsuk Fjord is a dolerite (number 5 on the map) which probably belongs to the second generation (possibly the third) and has been displaced 2.2 km: as no intersection has been found, the dating of this dyke is uncertain but its trend is the same as that of other dykes which definitely belong to the second generation. If the identification is correct it means that the displacement of second generation dykes decreases by 400 m from west to east.

As all the dolerite dykes which have been referred to are vertical or nearly so, the amount by which they have been displaced will be the same as the horizontal movement on the fault. No evidence has been found to show whether or not there has been any vertical movement on the fault during Gardar time, but as the flexure affecting the Ketilidian rocks seems to account for all the calculated vertical displacement, it is probable that only horizontal movement took place during the Gardar.

D. Other movement zones.

In addition to the Laksenæs fault, some other smaller faults are found in the area but these are all displaced by the latest movements on the big fault. The age of the smaller faults is uncertain but because of the different displacements of Kuánitic and Gardar dykes, it is apparent that they were active both before and during the Gardar period.

E. The youngest dolerite dykes.

The Laksenæs fault is cut by dolerite dykes which have a NNW trend which is parallel to the coast; these dykes are not displaced by the fault and are thus younger than the latest fault movements and have provisionally been ascribed to the Tertiary.

Conclusion.

In the area investigated, the Laksenæs fault clearly cuts Ketilidian structures and shows no relation to the Ketilidian folding, and so it is probable that the first movement along it took place after the Ketilidian period. Nevertheless it is still possible that the first movement took place toward the end of the Ketilidian period because, in the Ivigtut area, there are similar WNW trending sinistral wrench faults which have to some extent been controlled by Ketilidian structures. In one place the visible displacement on one of these faults ceases at the same time as the fault zone disappears into a thrust zone. In another case a WNW fault bends round to an ENE direction where it is controlled by the Ketilidian structure. In most cases however, the WNW trending faults cut through the Ketilidian structures and are clearly later than these. In the cases mentioned in which there has been apparent control by Ketilidian structures, the difference may be due to local variation of the regional stress conditions. Where a fault is almost parallel to the earlier structures, as is the case in the two examples given, it is probable that the stress conditions are altered so that the fault will follow the bedding or foliation direction.

An important feature of the Laksenæs fault is its step-wise development in which the displacement of the Ketilidian gneisses represents the sum of the three partial displacements. Each partial displacement took place in its own geological period with approximately 1.5 km horizontal displacement before the Kuánitic period, about 1.5 km during the Sanerutian, and 3.0 km during the Gardar. There was also a vertical displacement of about 2 km which took place probably before the Gardar period. As the somewhat schematic outline of the development which is given above is not quite certain, some further comments are given below.

In the area south of Ivigtut it has been shown that there is a generation of amphibolitised dykes which is younger than the earliest Sanerutian deformation. If this chronology is transferred to the northern area where there is usually no trace of the Sanerutian deformation, it is seen that some of the dykes which have been regarded as being of Kuánitic age, may possibly belong to the Sanerutian. As none of the older amphibolitised dykes which are definitely of Kuánitic age have been correlated across the fault and the displacement has been measured on one of the later ones, it is then possible that the first movement on the fault did not take place until the Sanerutian period. Thus the first movement may have taken place at the same time as the early Sanerutian deformation, with a second movement in the late Sanerutian time and after the intrusion of the youngest generation of amphibolitised dykes. Movement in the early part of the Sanerutian would then account for the displacement of the gneisses being greater than that of the younger amphibolitised dykes, and movement in the later part of the Sanerutian would then be responsible for the amount by which the displacement of these younger dykes exceeds that of the Gardar dykes. This means that the movements on the fault may have taken place in only two geological periods, namely 1/ two phases of Sanerutian movement, and 2/ Gardar movements. No evidence can be found to test the correctness of these suggestions as it is not possible to determine the age of the correlated dyke relative to the Sanerutian deformation. However the dyke is most probably of Kuánitic age, as the only late Sanerutian dykes which have been found in the area to the south are rather thin and irregular.

Where the buckling of the Ketilidian gneisses has taken place the Gardar dykes are vertical, and so it is likely that the buckling took place before the Gardar period and, therefore, that there was no vertical movement during the Gardar. It is not known whether or not the Kuánitic dykes have been affected by the buckling which affects the gneisses, and so the buckling may have taken place in either pre- or post- Kuánitic time. The variation in the displacements of Gardar dykes shows that the Gardar movement took place in two stages. The later of these two stages is known to have taken place after the intrusion of the third generation of dolerites, while the earlier stage is only known to have taken place at some time before the intrusion of the third dyke generation.

A dyke which is affected by both Gardar movements is displaced 800 m more than a dyke which has been affected only by the later movement and it is also found that the total displacement decreases towards the east, which is consistent with the relatively small displacements found on the east side of Arsuk Fjord where the Grønnedal Syenite, which is of early Gardar age, has been displaced only about 1 km. The displacement of the Ketilidian and Kuánitic rocks in the area on the east side of Arsuk Fjord is not known accurately but is estimated to be about the same as that of the Gardar rocks.

The big difference in the size of the displacements on the two sides of Arsuk Fjord can be explained in the following way. The fault movement originated, after the Ketilidian, in the area on the west side of the fjord but without any movement, at this time, on the east side of the fjord. This suggestion is confirmed by the fact that in the area east of Arsuk Fjord the fault plane, unlike the Kuánitic dykes here, is not folded. This localisation of the movements persisted until Gardar time when the fault was extended to the east of the fjord where, as has been pointed out, the displacement is less than that found further to the west. This decrease in the amount of the horizontal component towards the east must be considered in relation to the buckling of the southern block, which resulted in the vertical displacement but which must also have caused a decrease in the horizontal displacement towards the east.

No movement took place along the fault in post Gardar time during which a set of NNW trending dolerite dykes was emplaced. As has been mentioned, these dykes are probably of Tertiary age and are remarkable because of their coast parallel trend which has been observed on a regional scale.

Petrographical examination of rocks from the neighbourhood of the fault has shown that the effects of the fault movements on them, were quite small. All the cataclastic features which have been seen are of post Sanerutian age and it is most likely that Sanerutian regional metamorphism destroyed all traces of earlier cataclastic movements. Examination of thin sections has shown that the recrystallisation seams along the micro-faults were formed at an early stage which was followed by the formation of breccias and, still later, the formation of quartz, epidote, and calcite veins, while chloritisation of the dark minerals took place before the formation of the veins. It has not been possible to correlate the features seen in the thin sections with the different phases of movement, but it is assumed that all the cataclastic features are the result of Gardar movements, which are the only ones which took place after the second regional metamorphism. The alteration of the dark minerals to chlorite suggests that the latest movements took place at quite a high level in the earths crust.

As can be seen from the above, there are so many uncertain features in the investigation that conclusions can be drawn only with certain reservations and can therefore better be regarded as possible explanations.

Lastly, it should be mentioned that in the area dealt with, the Laksenæs fault is not affected by Gardar mineralisation which is often controlled by older fault zones in areas to the south-east.

Copenhagen, November 1959.

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GRØNLANDS GEOLOGISKE UNDERSØGELSE
THE GEOLOGICAL SURVEY OF GREENLAND

MEDD. OM GRØNLAND BD. 162 NR. 9, II (NIELS HENRIKSEN). PL. 1.

GEOLOGICAL SKETCH MAP
of an area between
ARSUK FJORD AND KUÁNIT FJORD
SW GREENLAND