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SUPERPOSED DEFORMATIONS OF THE KETILIDIAN GNEISSES IN THE SÂRDLOQ AREA, SOUTH GREENLAND

BY

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WITH 27 FIGURES AND 1 TABLE IN THE TEXT, AND 3 PLATES

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Abstract

A large part of the Sârdloq area comprises intercalated horizons of homogeneous gneiss, veined gneiss and banded gneiss of Precambrian age. The gneisses were deformed during the Ketilidian orogeny by three phases of folding, F_1–F_3. F_1 are in the form of mesoscopic intrafolial folds in varying states of preservation within the regional foliation, S_1. F_2 are mesoscopic and macroscopic folds that have a shallow plunge to the NE and SW, where unaffected by the third folding. Asymmetrical, similar, disharmonic folds with curviplanar axial planes but constantly oriented axes are the characteristic F_2 structures formed under strong lithological control mostly in the veined gneiss horizons under syn-migmatisation and amphibolite facies conditions. The crystallisation of constituent minerals taking place under syn- to post-kinematic conditions outlasted the deformation. S_2 axial plane structures are rarely developed. F_3 folds have a constant orientation with vertical axial planes and plunge variably to the NW or SE. The F_3 folds are in the form of a macroscopic buckling of the S_1 foliation formed under post-migmatisation and epidote-amphibolite facies conditions. A tectonic mélange was locally formed in response to the third phase movements.

A structural correlation is made with neighbouring areas. It is suggested that the metamorphism and migmatisation are diachronous with respect to the fold phases, arriving during the third folding at a higher level in the Nanortalik area to the SE.

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I. INTRODUCTION

The Sârdloq area lies in South Greenland immediately to the south of Julianehåb (see plate 1). It embraces an area of about 640 sq. km, of which approximately half is covered by water, and it comprises three main peninsulas and about 270 islands. Sârdloq village is situated in the south-western corner of the area.

The mapping of the Sârdloq area was carried out during the summers of 1960–62 as part of the coordinated mapping of South Greenland by the Geological Survey of Greenland (GGU) and the results were used for a doctorate thesis in the University of Exeter (WINDLEY, 1963). Part of the work was undertaken in the University of Copenhagen during receipt of a Danish Government Scholarship. A small part of the thesis was devoted to a structural analysis of the area, which forms the basis of the present study. The writer is grateful to Dr. A. K. HIGGINS, Mr. E. BONDESEN and Dr. J. ALLAART for helpful criticisms, to Dr. A. ESCHER for help with the structural stereogram, to the GGU geologists in the Julianehaab-Frederiksdal district for permission to publish their structural data for the correlation map (plate 1), and to K. ELLITSGAARD-RASMUSSEN, Director of GGU, for permission to publish this paper.

Regional Geological Setting

For a synthesis of the geology of the Sârdloq area the reader is referred to WINDLEY (1966). For the purposes of a background to the present study a summary is given of the surrounding geology.

The rocks of South Greenland have been subdivided chronologically by members of GGU into five periods: the pre-Ketilidian, Ketilidian, Kuanitic, Sanerutian and Gardar.

During pre-Ketilidian time an original supracrustal series was metamorphosed under granulite facies conditions giving rise to a stratigraphic succession of gneiss, amphibolite, anorthosite and ultrabasic horizons, all folded during at least three phases of deformation. These rocks were later intensely retrograded under conditions of the amphibolite facies and the epidote-amphibolite facies (WINDLEY, 1964).

During the early part of the Ketilidian period a supracrustal series was laid down on the pre-Ketilidian basement and there was intrusion of basic dykes. During the plutonic phase of the Ketilidian the sediments were metamorphosed, gneissified and deformed by at least three phases of folding.

The Kuanitic period was marked by a return to a cratogenic environment when dykes of basaltic parentage were intruded under tensional conditions.

During the Sanerutian there was a return to plutonic conditions when the earlier gneisses and granites were partially to completely reactivated to form a new series of granitic rocks, in which the earlier basic dykes were preserved as relics. Also during the Sanerutian emplacement of the following rocks took place: synplutonic basic dykes, net-veined diorites, the "New granites", homogeneous microgranites, pegmatites, aplites and basic dykes.

During the Gardar period supracrustal rocks were deposited, a suite of alkaline to basaltic rocks was intruded in the form of layered plutons and dykes, and there were extensive faulting and mylonitisation.

In post-Gardar time a swarm of dolerite dykes was emplaced.

The chronological succession of events in the Sârdloq area is as follows:

POST-GARDAR	Intrusion of dolerite dykes
GARDAR	Intrusion of dolerite dykes; faulting and mylonitisation
SANERUTIAN	Intrusion of basic dykes Formation of pegmatites and aplites Emplacement of homogeneous microgranites Intrusion of net-veined diorites Intrusion of basic dykes under late synplutonic conditions Reactivation and metamorphism under amphibolite facies conditions
KUANITIC	Intrusion of doleritic dykes and basic to ultrabasic bodies
KETILIDIAN	Gneissification, migmatisation, metamorphism under amphibolite facies and epidote amphibolite facies conditions and formation of three phases of folds Intrusion of basic dykes Deposition of supracrustal series

Throughout this paper the gneisses of the Sârdloq area are said to be of Ketilidian age. However, it is admitted that the presence of reworked relics of pre-Ketilidian basement cannot be excluded, but with the evidence available at present the writer considers that this is highly improbable.

The Sârdloq area has a critical position, as it lies astride a reactivation front between the highly folded Ketilidian gneisses to the south and the granites to the north reactivated during the Sanerutian. The present study is an attempt to obtain a systematic picture of the structural evolution of the Ketilidian fold belt within the area around Sârdloq. The structural development of the gneissic series is one of the most important aspects of the Ketilidian fold belt.

II. LITHOLOGY AND PETROGRAPHY

There are three types of gneiss in the Sârdloq area. For the purposes of general description the definitions laid down by the recent symposium on migmatite nomenclature (Sørensen, 1960) are referred to. In this symposium Berthelsen has given the gneiss classification used by members of GGU in South Greenland as follows:

"A banded gneiss is made up of alternating, well defined layers of different composition. In thinly banded gneisses, the individual layers are less than 1 centimetre thick, whereas in the giant-banded ones they are more than half a metre thick."

"In veined gneiss the pattern is characterised by sub-parallel to branched, discontinuous and more or less irregular, light coloured veins rich in quartzo-feldspathic material."

"Homogeneous gneiss has no banding, but shows preferred orientation of the mafics. Lithologically it is homogeneous".

These general definitions are approximately correct for the three gneiss types of the Sârdloq area.

Succession

Near Sârdloq the gneisses form a succession of intercalated horizons (plate 2). Five horizons of veined gneiss alternate with four of homogeneous gneiss and these are followed by a banded gneiss horizon, which is up to 300 m in width, while the narrowest veined gneiss horizons are only a few metres wide. It has been possible to trace the horizons along their strike in a north-easterly direction for a distance of 20 km from Sârdloq.

In the north-east corner of the area on the peninsula on which Nunarssuaq is situated there is a succession of eleven horizons which are traceable for about 12 km along their strike (plate 2). Homogeneous gneiss is mostly intercalated with banded gneiss horizons together with two horizons of veined gneiss. Individual horizons vary from several tens of metres to more than a kilometre in width.

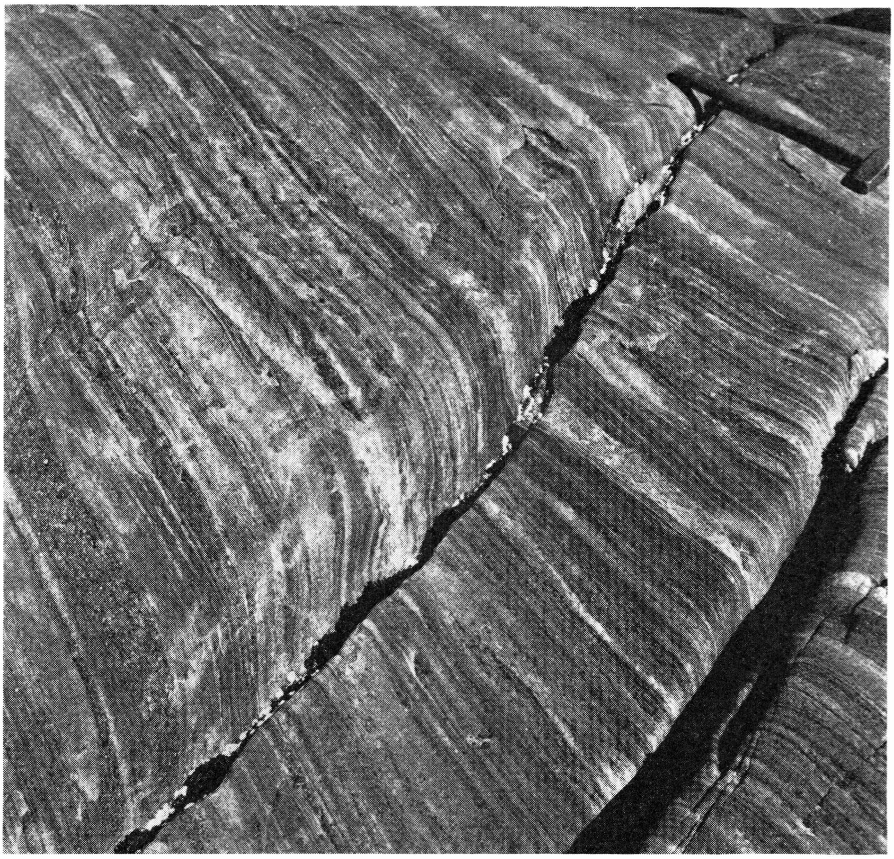

Fig. 1. Banded gneiss composed of alternating hornblende-rich and quartzo-feldspathic bands defining the regional foliation, S_1. There are some leucocratic veins that cross-cut the banding at a low angle.

The homogeneity of the three rock types has enabled them to be identified over considerable distances. Although the rocks may be inhomogeneous within themselves, their internal structures such as banding, foliation, or porphyroblastic nature are uniformly developed over large areas. It is this homogeneity which has made it possible to map a stratigraphy in the Ketilidian gneisses and consequently to unravel their structure.

There are no indubitable metasedimentary or metavolcanic relics within the gneisses of the Sârdloq area. The presence of rare pods and lenses of skarn pyroxenite, not more than 30 cm in length, suggests the existence of former calcium-rich horizons.

i) Banded Gneiss

The banding forms a well-defined planar structure (fig. 1) which is composed of continuous alternate hornblende-rich and quartzo-feldspathic bands; a few biotite-rich bands occur in places. The bands vary in width from about 1–40 cm, although there are some granitic and amphibolitic films only a few millimetres wide. The rock presents a very regular appearance due to the prevalent continuity and straightness of the bands together with the general absence of minor folding.

The acid bands are composed of quartz, plagioclase (oligoclase), and microcline and have a xenomorphic-granular texture. The grain size is less than 4 mm. There are common porphyroblasts 2–4 mm in size of plagioclase (oligoclase) and microcline. In places they are in roughly equal proportions in individual layers, but often plagioclase predominates and to such an extent that some layers contain only plagioclase porphyroblasts. There is usually a small amount of biotite.

The basic bands contain essential clinopyroxene, hornblende, biotite, chlorite and epidote; in addition there is some plagioclase (andesine), quartz and microcline. Accessories, which are mostly confined to the basic bands, include sphene, apatite and ore. The grain size of less than 1 mm is considerably less than that of the acid bands. There are a few plagioclase and microcline porphyroblasts. The hornblende is partly retrogressive after clinopyroxene, biotite is mostly primary, chlorite is after hornblende, and plagioclase is sericitised. Epidote occurs in two generations. The first occurs as small granules interstitial between hornblende and plagioclase, whilst the second forms larger grains and irregular masses which cross-cut and dismember earlier minerals, especially the hornblende and plagioclase.

ii) Veined Gneiss

The gneissic banding is composed of discontinuous, alternate granitic and micaceous bands which vary from a few centimetres to about 30 cm in width. It is common for the bands to thin and thicken over short distances. The rock presents a very irregular appearance due to the abundance of plastic folding and minute crumpling and to the discontinuity of the bands (fig. 2). Individual horizons thin out along their strike more rapidly than do those of the other two gneiss types.

Acid bands are comprised of plagioclase (oligoclase), quartz and microcline and the basic bands of biotite, muscovite, chlorite, epidote and hornblende with some plagioclase and quartz. Accessories are sphene and ore. The most conspicuous megascopic feature of the gneiss is the presence of abundant plagioclase porphyroblasts which are commonly augen-shaped. Chlorite is secondary after biotite, and hornblende is rare.

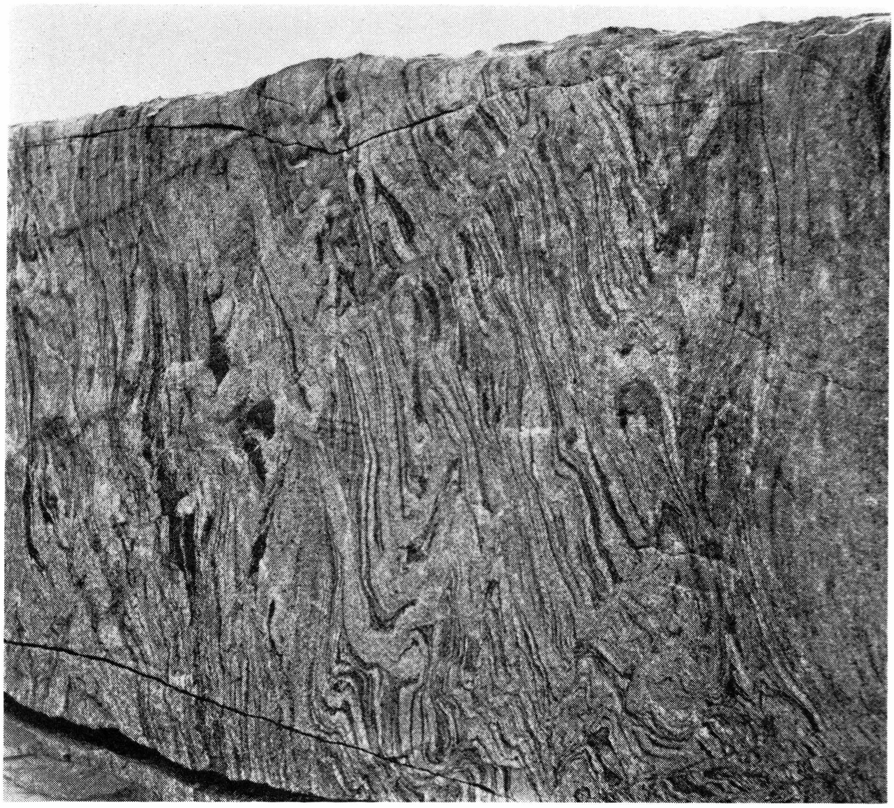

Fig. 2. Highly deformed veined gneiss composed of alternating thin micaceous and quartzo-feldspathic layers defining the S_1 foliation. Just below the centre of the photograph it can be seen that the granitic neosome passes along the axial planes of the folds which are of F_2 age. The folds are of similar type and have a plastic style with curviplanar axial planes. Approximately profile view. The height of the wall is about 2 m.

iii) Homogeneous Gneiss

This gneiss, which has no compositional banding, has a foliation expressed by the linear orientation of hornblendes and by the planer orientation of feldspar porphyroblasts and biotites (fig. 3). The porphyroblasts are of plagioclase and potash feldspar, which form sub- to euhedral crystals mostly with their longest axes in the plane of the foliation, but a few lie in an oblique position.

Constituent minerals include plagioclase, microcline, quartz, biotite, hornblende and epidote. Accessories are allanite, apatite, pyrite, haematite and ore. The texture is xenomorphic-granular and the grain size is less than 1.5 mm, but porphyroblasts attain a maximum size of 4 cm. Chlorite has formed retrogressively from biotite.

Fig. 3. Typical homogeneous gneiss that has no banding. The long axes of feldspar porphyroblasts mostly lie in the plane of the S_1 foliation, but a few can be seen to cut across it. The length of view is about 2 m.

Metamorphic Facies

The gneisses of the Sârdloq area were constituted during two periods of regional metamorphism. The acid and basic bands of the gneisses have the following mineral assemblages:

Acid Bands	*Basic Bands*
Oligoclase-microcline-quartz	Clinopyroxene-hornblende Hornblende-biotite-andesine-(epidote)
Subsidiary hornblende and biotite	Biotite-(chlorite) Biotite-muscovite-(chlorite) Chlorite
	Subsidiary microcline and quartz

Accessories are sphene, orthite, apatite and ore (pyrite, haematite and magnetite).

Garnet, hypersthene and the alumino-silicates are entirely absent.

The primary mineral assemblages, characterised by the development of clinopyroxene, hornblende, biotite, epidote, andesine, microline and quartz, crystallised under P/T conditions belonging to the staurolitequartz subfacies of the garnet-amphibolite facies as defined by FYFE, TURNER and VERHOOGAN (1958, p 229).

Extensive chlorite and a second generation of epidote formed retrogressively from the earlier mineral assemblages under lower P/T conditions corresponding to the epidote-amphibolite facies. The two periods of metamorphism are considered to have formed in association with the F_1/F_2 and F_3 phases of folding respectively.

III. STRUCTURE

Introduction

Detailed structural observations in the Sârdloq area have established the presence of three generations of folds.

a) Rootless intrafolial folds often in tectonic inclusions within the regional foliation.
b) A widespread plastic folding of the regional foliation which took place largely in the veined gneiss horizons.
c) A large-scale buckling of the foliation with variably plunging axes.

There is a single set of planar parallel surfaces (the regional foliation) throughout the area, which have a general north-easterly strike and a shallow to steep dip to the north-west.

The area has been divided into 32 sub-areas in each of which some degree of uniformity of structural style has been recognised (plate 3). This is expressed by a statistically homoaxial or biaxial homogeneity with respect to the last two generations of structures within each sub-area. It has been found necessary to reduce the structural measurements to so many sub-areas because the intense structural inhomogeneity, particularly in the north-east of the area, has given rise to a high degree of spread of all structural elements. On all scales from the smallest to the largest the structures mostly have a triclinic fabric, thus planes of symmetry are uncommon. This is the consequence of two factors; firstly, the intense apparent "wildfolding" (it will be shown later that this term is inapplicable and that such folding does not occur) formed during the second fold movements and secondly, the superimposition of the third generation structures on those of the second generation. It is thus common, for example, to observe plastically deformed, asymmetrical, overturned, disharmonic, minor folds with axes varying from steep to shallow and a regional foliation which twists and buckles in a plastic manner with no apparent geometrical regularity. This type of tectonite fabric is common to the gneisses of the highly migmatised infrastructure and it is surprising that little attempt has been made by structural geologists to unravel this type of tectonite. The structural study by Ramsay (1958 b) of the Lewisian migmatites at Glenelg in NW Scotland is a notable exception to this. The quickly discernible geometrical regularity of superposed folds in rocks of the non-migmatised superstructure is relatively easy to comprehend in comparison with the apparent wild-folding frequently observable in infrastructural gneisses which at first sight tends to defy geometrical analysis. This study has been carried out with the basic assumption that these rocks can be subjected to a geometrical analysis (see also Berthelsen, Bondesen and Jensen, 1962). Although this does give a general and preliminary insight into the structural development of the Ketilidian fold belt in this area, it cannot explain many of the heterogeneities and irregularities of minor folds which at best can only be pigeonholed as "flow-folds".

In recent years there have been numerous studies of superposed fold structures (Weiss and McIntyre, 1957; Ramsay, 1958 a). These were based on the tectonic method of Sander (1948). The first and major part of this method involves the determination of the geometrical co-ordinates of the different sets of superposed folds from which it may be possible to determine the kinematic co-ordinates of the responsible stress fields.

Terminology

The following terminology based on that of Sander (1948, p 132) is assigned to the structures under discussion:

Planar Fabric Elements

- S' = the set of surfaces forming the limbs of the F_1 folds.
- S_1 = the set of planar surfaces forming the regional foliation and compositional layering of the area and occupying an axial plane position to F_1 folds. S_1 planes lie parallel to the boundaries of the lithological horizons.
- S_2 = the set of surfaces sub-parallel to the axial planes of F_2 folds.
- S_3 = the theoretical axial surfaces of F_3 folds, which are north-westerly striking planes in which the F_3 axes lie.

Fold Nomenclature

- F_1 = the first phase folds in S', with S_1, the regional foliation, as the axial plane.
- F_2 = the second phase folds in S_1, with S_2 as the axial plane. A lineation marked by crumpling on the S_1 surfaces lies parallel to the F_2 axes.
- F_3 = the third phase folds in S_1 with S_3 as the theoretical axial plane.
- β (i. e. βS_1) = the pole of an S-pole girdle. β is not used to define the intersection of tautozonal S-surfaces.

The stereograms on plate 3, showing the preferred orientation of the main structural elements of the area, are lower hemisphere plots on an equal-area projection. The stereograms are π diagrams, in which the poles of S_1 planes (π S) define an S-pole girdle. The great circle in each diagram is the circle of best fit to the poles of the measured S_1 planes and the pole of this great circle defines the fold axis and is designated β according to customary practice. However, following the suggestion of TURNER and WEISS (1963, p 155) that "π be dropped from the terminology of structural analysis", on account of the current confusion in its usage, and having already heard of "the last of π" (LINDSTRÖM, 1959), this term will not be used in the following discussion.

The terms microscopic, mesoscopic and macroscopic are used after the definitions of WEISS and MCINTYRE (1957, p 577) and TURNER and WEISS (1963, pp 15–16):

microscopic – the field of a microscopic thin section.

mesoscopic – the directly observable fields ranging from hand specimens to single or continuous exposures.

macroscopic – fields too large or discontinuous to be observed directly, in which the overall structure can only be ascertained by indirect methods.

Description

i) Mesoscopic Scale

First Phase Structures

Foliation. The regional foliation, S_1, is the most penetrative fabric of the area and is marked by slightly different characteristics in the three gneiss types, although it is essentially defined by the preferred orientation of inequant grains of mica, feldspar and hornblende. In the banded gneiss the foliation has the form of a parallel compositional planar layering composed of alternating amphibolite and quartzo-feldspathic layers (fig. 1). There is a higher degree of mineral orientation in the basic than in the acid layers. In the veined gneiss the foliation is marked by sub-parallel thin discontinuous wisps, stringers and streaks of granitic material separated by compact micaceous layers comprising well-oriented muscovite and biotite (Fig. 2). There are also feldspar augen, the longest axes of which lie in the plane of the foliation. In the homogeneous gneiss the foliation is largely expressed by the preferred dimensional orientation of feldspar porphyroblasts, the longest axes of which lie in the foliation plane (fig. 3). Mica also has a preferred orientation which is less marked than that of feldspar.

Where unfolded by F_3, the foliation has a NE-SW orientation. The effect of the third period of folding has been to give S_1 a variable strike.

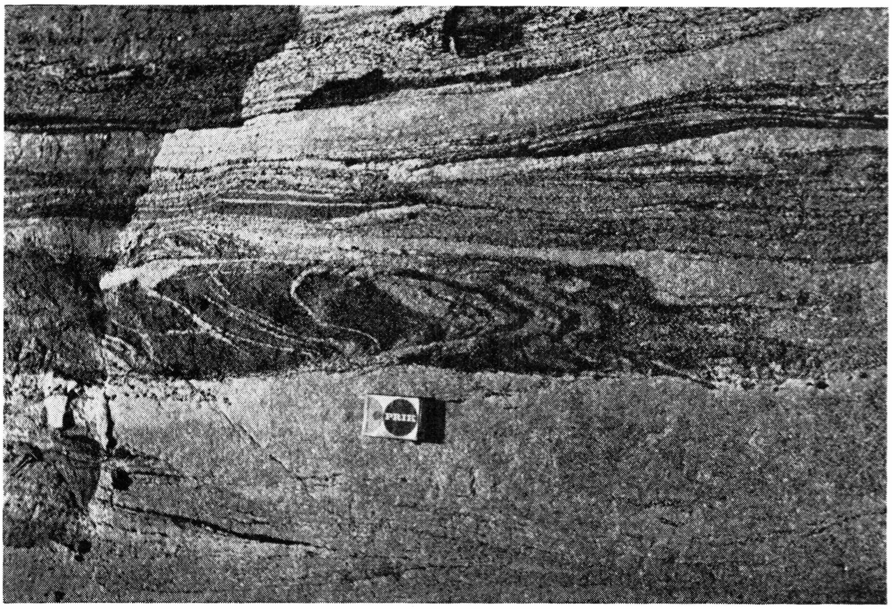

Fig. 4. An intrafolial F_1 fold occurring in an amphibolitic lens in banded gneiss. The fold axis plunges shallowly to the right.

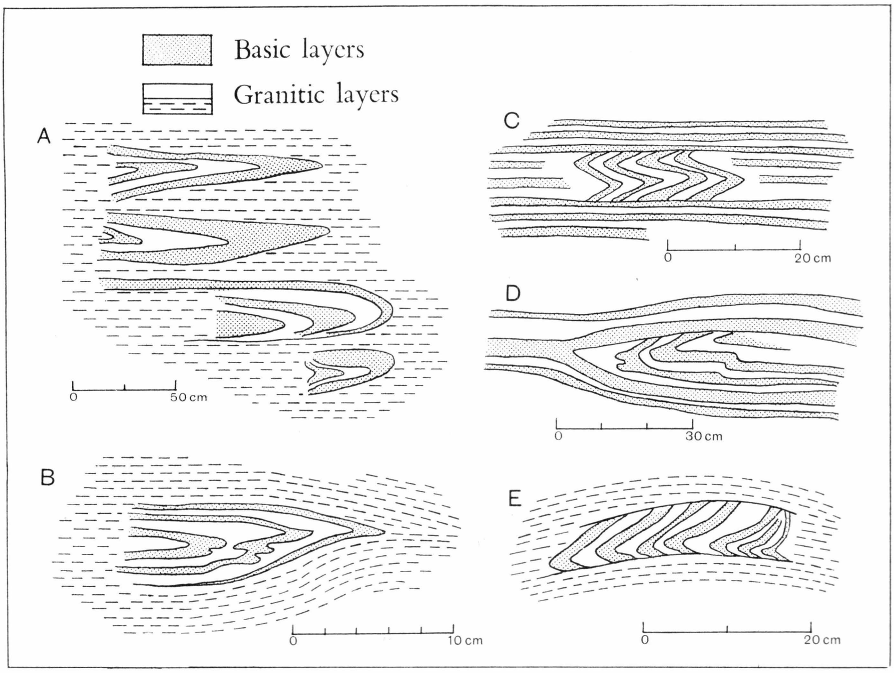

Fig. 5. Sketch diagrams of intrafolial F_1 folds in five different localities. A and B are in homogeneous gneiss, C and D in banded gneiss and E in veined gneiss. The folds vary in style from relicts with limbs (S') parallel to S_1 (A and B), to those in which the limbs (S') are truncated by S_1 (C, D and E). In all examples the axial planes of F_1 are parallel to the enclosing S_1.

Fig. 6. Profile view of an intrafolial F_1 fold in homogeneous gneiss. S_1, the regional gneiss foliation, is defined by elongate and augen-shape feldspar porphyroblasts. The axial plane and the long limbs of the fold are parallel to S_1.

Folds. Folds formed during the first phase of folding, designated F_1, are rare in the Sârdloq area. As will be shown later in section IV, they also appear to be rare in the surrounding areas and their presence is critical in the understanding of the first observable phase of folding.

F_1 folds are rootless intrafolial folds (Turner and Weiss, 1963, pp 116–117) occurring commonly in tectonic inclusions within the regional foliation, S_1 (fig. 4). They are usually tight (sometimes asymmetric) to isoclinal folds, the style of which can be seen in fig. 5. They are similar folds with thickened hinges and attenuated or sheared-out limbs. The long limbs defined by S' may be parallel to (fig. 6) or truncated by S_1 (fig. 7). A less advanced stage in the obliteration of F_1 is shown in fig. 8 in which the regional foliation occurs as an axial plane structure of the folds. The length of the long limbs from closure to closure varies from about 5 cm to about 1 m. S_1 consistently has an axial plane position to F_1, whatever its orientation. Some folds are merely single closures, so that their direction of vergence, or the full style of the folds, cannot be seen. Some appear as isoclinal to tight folds enclosed

Fig. 7. Profile view of an intrafolial F_1 fold in homogeneous gneiss. The fold limbs, S', are truncated by S_1, the regional foliation. The folds are of similar type with strongly thickened hinges and attenuated limbs. It can be seen that S_1 is in the process of development within both the quartzo-feldspathic and micaceous layers of the folds.

within S_1. F_1 axes vary in plunge and axial trend according to the orientation of the enclosing S_1. Where unaffected by the F_3 folding, they plunge at shallow to moderate angles to the NE or SW. Likewise the attitude of the axial plane varies according to the amount of dip of S_1.

Like most mesoscopic folds, the F_1 folds have been observed and studied on the well-exposed, lichen-free coasts of the area. This has not only made it difficult or impossible to obtain specimens of the folds, but it has also frequently prevented measurement of the fold axes on the planar polished surfaces.

Second Phase Structures

Folds. The majority of folds of the second phase, F_2, occur in the veined gneiss horizons, some in the banded gneiss but few in the homogeneous gneiss. They are most intensely developed in the SW of the area

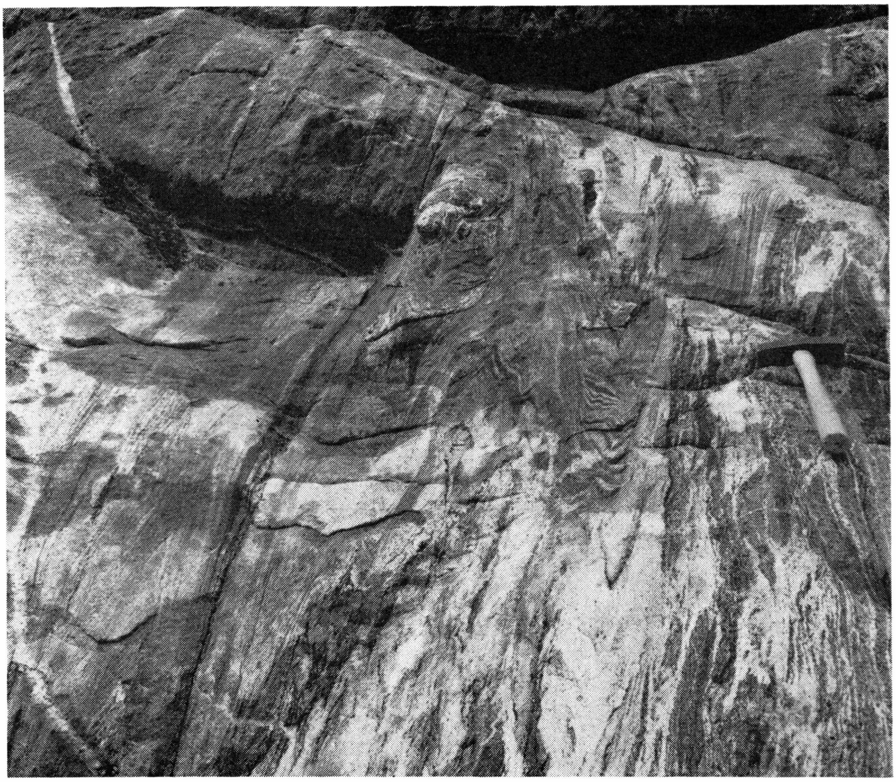

Fig. 8. Profile view of F_1 folds in banded gneiss in a less advanced stage of obliteration to those shown in the preceding four figures. In the top left corner of the photograph the regional foliation is typically developed, though with no banding. In the bottom left corner small discordancies can be seen which may be the only surviving remains of an early F_1 fold.

where the veined gneiss horizons are most common and at their widest. F_2 is characterised by a plastic style of folding and results therefore in similar folds with strongly thickened hinges and thinned limbs. Many folds fit the description of flow-folds due to their apparent plasticity and irregularity of style. They are symmetrical to asymmetrical folds overturned to the SE with north-westerly inclined axial planes. The trend of fold axes varies according to the position on the F_3 fold limbs. Where unaffected by F_3 folding axes plunge shallowly to the NE and SW. F_2 folds occur on all scales from minute plications only a few centimetres in size to minor folds which most commonly have a wavelength (or distance between two complementary closures) of about 10–40 cm and an amplitude of 5–40 cm. Parasitic minor folds conform with Pumpelly's rule with respect to their larger, parent, major folds. "The degree and direction of pitch of a fold are often indicated by those of

Fig. 9. F_2 folds in veined gneiss in which layers of differing competency have deformed disharmonically. Profile view.

the axes of the minor plications on its sides" (PUMPELLY, WOFF and DALE, 1894). This axial regularity applies on all scales of observation from the mesoscopic to the macroscopic.

Disharmonic folds are ubiquitous, particularly where rigid amphibolitic bands are intercalated with more incompetent mica-rich gneiss (fig. 9). In similar rocks "arrow-head" structures are common:-fold cores outlined by pointed arrow-like fragments of basic rock in a gneissic framework. (KRANCK, 1957). In some places competent amphibolitic bands have been broken in the hinge zone of a gneiss fold.

It is a common feature for F_2 axial surfaces to be non-parallel and curviplanar (fig. 10). Curviplanar surfaces may be either parallel or non-parallel (fig. 11), thus complementary surfaces may curve away from each other. Folds with extremely curved axial surfaces appear superficially to have been refolded (fig. 12). In groups of minor folds with highly curved and divergent axial surfaces, it is significant that F_2 axes have a fairly constant azimuth and plunge. This is illustrated in fig. 12 from a study of minor folds near Sârdloq village.

In the plastically deformed veined gneisses there are conjugate and box folds of F_2 age. They occur in association with the curviplanar and non-parallel axial planes as can be seen in examples A and B of fig. 11. Axial planes are inclined towards each other at angles varying from acute to 90°. There are some structures that can best be termed reversed

Fig. 10. F_2 folds in veined gneiss. The axial surfaces of the folds are highly curviplanar which is a characteristic of this plastic style of folding of F_2 age.

conjugate folds (fig. 11 c). The most significant geometrical feature of the conjugate folds is that their axes are mutually parallel, coincident with the surrounding minor F_2 axes. This indicates that the line of intersection of the conjugate axial planes is coincident with the fold axes thereby defining an orthorhombic structure (Ramsay, 1962 a). This demonstrates that the kinematic axes of the stress system also had orthorhombic symmetry, the minimum principal stress axes lying normal to the surface being folded.

It is rare to find examples of refolded folds in the Sârdloq area. Fig. 13 shows a F_2 fold core in which there lie some F_1 folds which are rootless, tight to isoclinal, intrafolial folds, similar to those previously described. The axial planes of F_1 are parallel to S_1. No examples have been observed on a mesoscopic scale of F_3 folds refolding either F_1 or F_2 folds.

Two refolded isoclines are shown at points X and Y in fig. 12. These occur in plastically deformed veined gneiss in which F_2 folds have

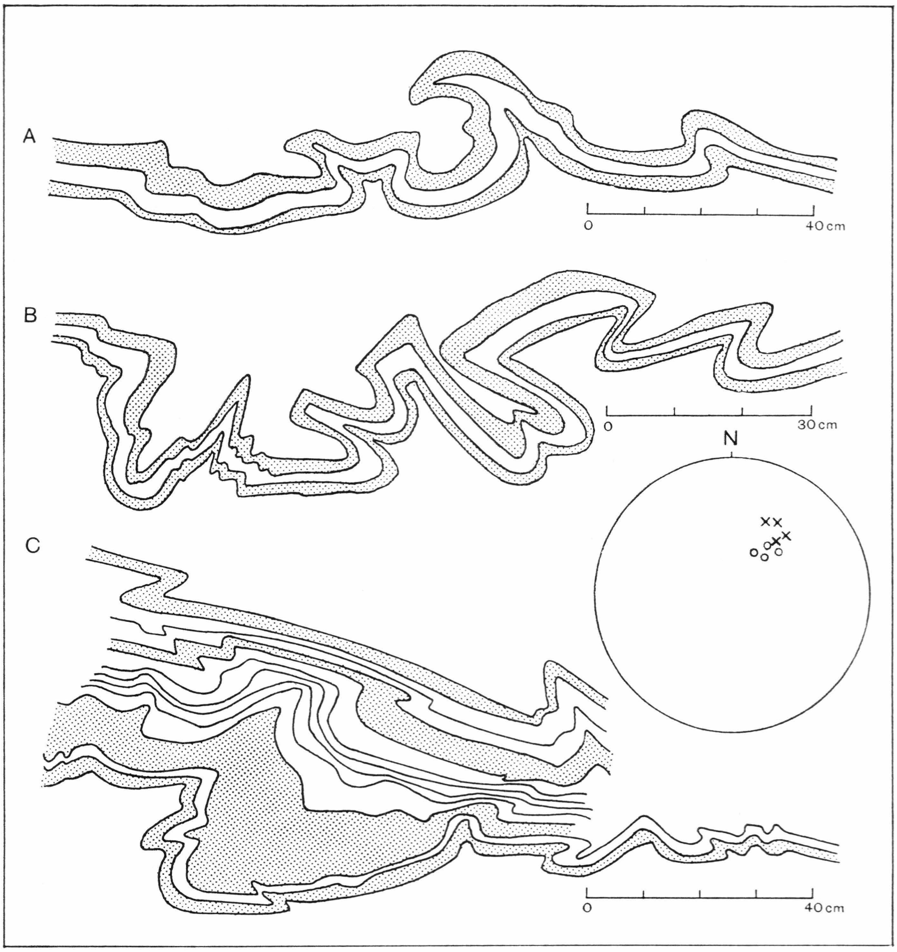

Fig. 11. Drawings of three groups of F_2 folds in veined gneiss. A and B are only a few metres from each other near Sârdloq village. The axial surfaces are highly curviplanar in A and non-parallel in B; but the measured fold axes are mutually parallel as is shown by the stereographic projection. There are conjugate folds in B and in C there are what might be termed reversed or composite conjugate folds. These features are characteristic of the veined gneisses highly folded with a plastic style. Profile view in all three examples.

highly curviplanar axial surfaces. The refolded isocline at Y lies near the termination of the thin amphibolite band. It is genetically significant that in both instances the axes of the refolded isoclines are coincident.

Parallel to the F_2 axes there is a lineation in the form of a fine corrugation or crenulation on the surface of S_1. Due to the common absence of S_2 and to the prevalent planar exposures on the polished coasts a lineation formed by the intersection of S_2 and S_1 is rarely observed.

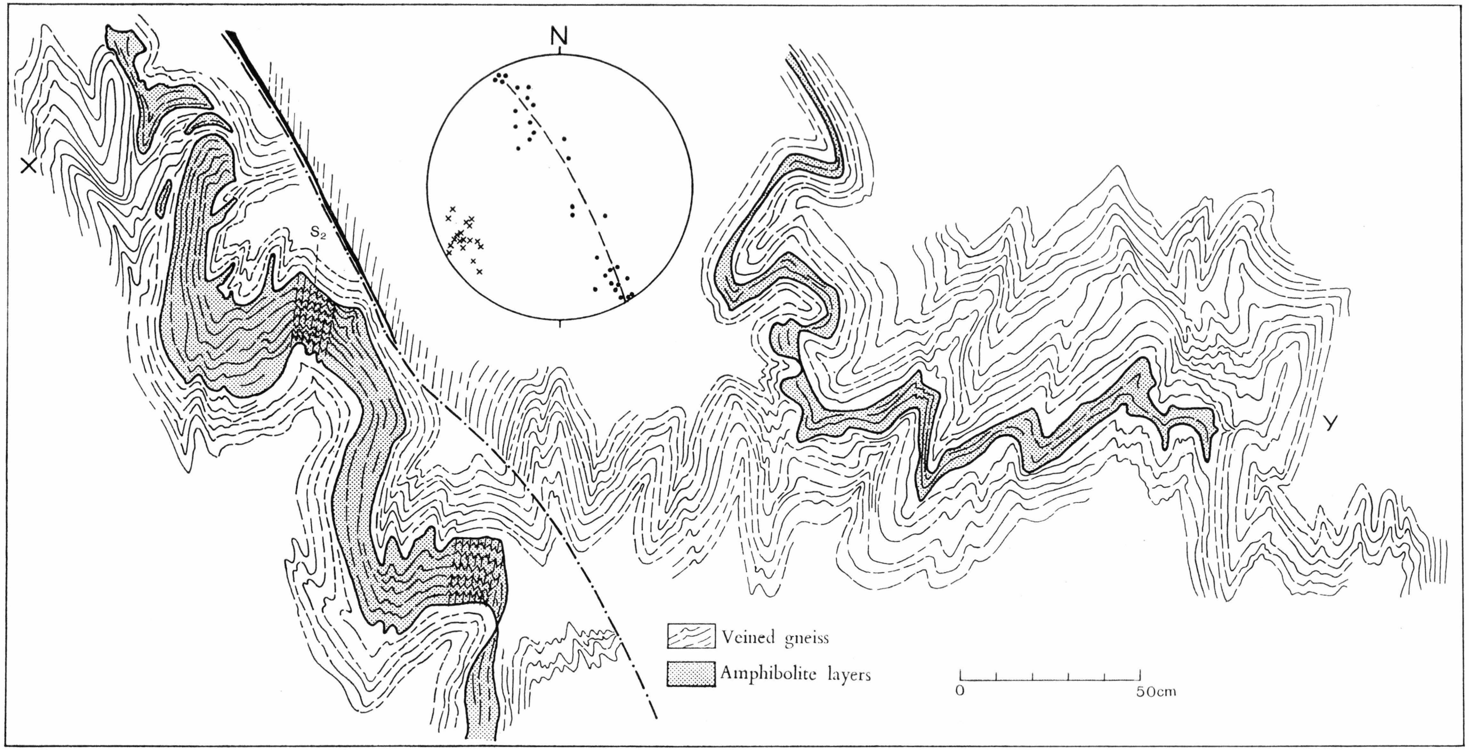

Fig. 12. Highly deformed veined gneiss. The folds are of F_2 age, many of which have curviplanar axial surfaces; however the stereographic projection shows that the fold axes are mutually parallel. There are two amphibolitic layers in which an S_2 cleavage has developed in the hinge zone of two folds. At points X and Y there are refolded isoclines with mutually coincident fold axes. The formation of the isocline at Y may have been controlled by the amphibolitic layer which terminates at this point. Both the isoclines and the later folds are considered to be of F_2 age. Crosses = fold axes; Dots – foliation poles.

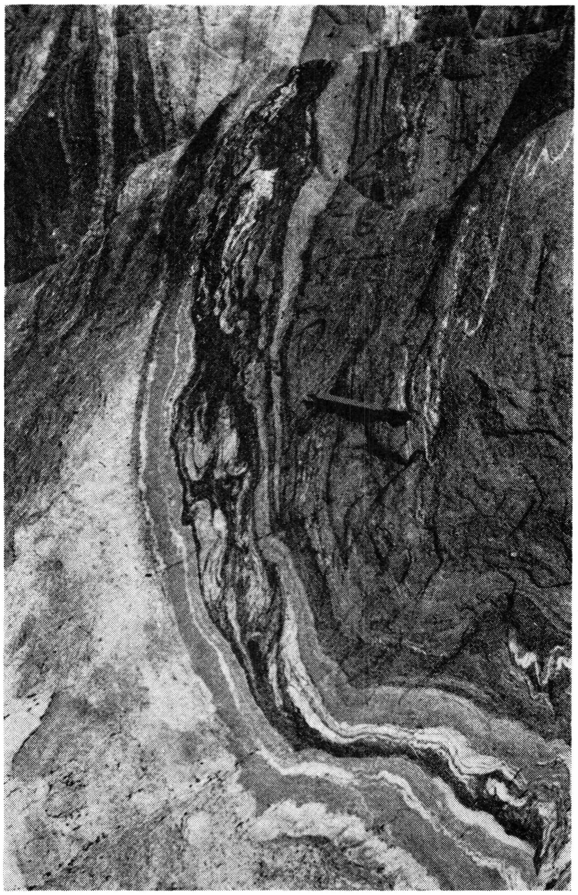

Fig. 13. Core of an F_2 fold with enclosed intrafolial F_1 folds. The F_1 have clearly been refolded by F_2. The axial surfaces of F_1 are parallel to S_1, the regional foliation of the banded gneiss. Approximately profile view of F_2.

The granitic neosome of the veined and banded gneisses is folded around the hinges of F_2. Also, veins of the granitic component pass, although rarely, along the axial planes of F_2 folds (figs. 2 and 14) or along transverse shears in the gneiss discordantly across S_1.

Cleavage. The majority of F_2 minor folds have no trace of a planar structure, S_2, parallel to their axial surfaces (figs. 2 and 10). This applies to folds in each of the three gneiss types, on all scales from the smallest plications to the largest mesoscopic folds and to all types of folds i. e. to angular chevron folds and to tight to isoclinal, similar folds.

Only in a few localities has an S_2 axial plane cleavage been seen. It appears to have a random distribution and has two forms:

Fig. 14. Profile view of an F_2 fold in veined gneiss. The granitic neosome clearly penetrates along the axial plane of the fold, demonstrating the syn-migmatitic age of the second phase of folding.

a) In folded micaceous amphibolitic layers enclosed in veined gneiss there is occasionally a cleavage formed of closely spaced planes in which biotite flakes are oriented (fig. 12). On an islet near Sánerut island there is a tight F_2 fold in gneiss composed of alternating amphibolitic and micaceous layers. In a single micaceous layer there is a well developed S_2 cleavage of strain-slip type (fig. 15). The fine crumpling has an amplitude between 0.25–0.5 cm but the fold limbs are transected by a transposed foliation in which the crumples either have been obliterated or are present as isolated rootless fold hinges.

b) In banded gneiss, a more competent rock than the micaceous layers just referred to, there is occasionally an S_2 fracture cleavage parallel to the axial surfaces of F_2 folds (fig. 16). The approximately planar surfaces are widely but variably spaced up to about 30 cm from each other. The gneiss foliation is dragged towards or parallel to the fracture surfaces within which there is in places a sigmoidal shear foliation.

In one locality near Sârdloq village there has been seen a new mineral growth defined by quartz and feldspar porphyroblasts aligned

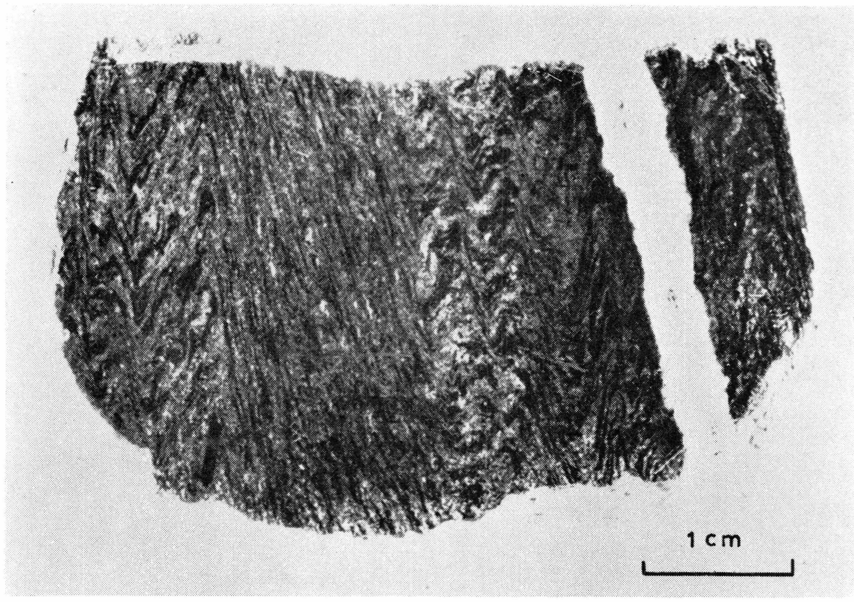

Fig. 15. A hand specimen of micaceous veined gneiss in which the S_1 foliation is cut by a new set of surfaces (S_2) formed along the axial planes of F_2 folds. The S_2 cleavage of strain-slip type has partially obliterated the F_2 folds. The specimen is taken from the core of a larger F_2 fold with an amplitude of about 2 m. Profile view. An islet near Sánerut island.

in a direction normal to the regional foliation of veined gneiss (fig. 17). The mineral lineation is situated in the hinge zone of a major F_2 fold and plunges 35° SW coincident with the local minor F_2 fold axes.

Third Phase Structures

Folds. The third phase folds, designated F_3, are mostly developed in the north-east of the area. However, F_3 occurs here usually on a macroscopic scale and thus mesoscopic folds of this age are rare. The few F_3 minor folds observed, as shown in fig. 18, are flexural slip folds in which single layers preserve their width around the fold closures. The folds have an open symmetrical style and measure between 0.5–1.5 m in wavelength and amplitude. Axial surfaces are vertical and parallel and axes plunge vertically or steeply to the north-west. F_3 folds have no planar structure parallel to their axial surfaces i. e. S_3 is not developed in the Sârdloq area. In hand specimen it can be seen that constituent mafic minerals (hornblende, biotite and muscovite) are folded around the hinges of F_3 folds: no recrystallisation is apparent.

Fig. 16. S_2 fracture cleavage in banded gneiss on Sánerut island. S_2 is parallel to the axial planes of F_2 and has caused drag and offset of the S_1 foliation.

Tectonic Mélange. In the veined gneiss of Sánerut island there is a mélange structure formed during the third folding movements. The gneiss occurs in broken angular segments which range in length up to several tens of metres. On badly exposed ground this type of structure appears at first anomalous, as the strike changes rapidly from outcrop to outcrop, yet no fold closures are visible. On Sánerut the late Sanerutian homogeneous microgranite, of which there are several large bodies in the vicinity, commonly forms veins or sheets between the thrust blocks masking the exact contact relations. However, in some places adjacent blocks with discordant strikes can be seen to abut cleanly against each other with no visible signs of shearing, deformation or recrystallisation between them, whilst in others the blocks are separated by zones up to 30 cm wide of sheared gneiss with a planar parallel fabric in which there is epidote and chlorite. Similar mélange structures

Fig. 17. A lineation of F_2 age defined by the alignment of quartz and feldspar porphyroblasts. The lineation, which cross-cuts the S_1 foliation of the gneiss, is situated in the hinge zone of a large F_2 fold.

observed by D. Bridgwater on Inuarutdligaq island in the neighbouring Sydprøven area to the east are illustrated in figs. 19 and 20. The rotated blocks occur in a 50 m wide horizon in the gneisses which can be traced for 0.5 km.

ii) Macroscopic Scale

The form of macroscopic structures can be determined in two ways: (1) from the pattern of surfaces between rock types expressed by the geological map; (2) from a study of the geometry of sub-areas expressed by stereographic plots of the various structural elements.

It must be remembered that the geometrical information gained from the stereographic plots gives an unrepresentative picture of the macro-

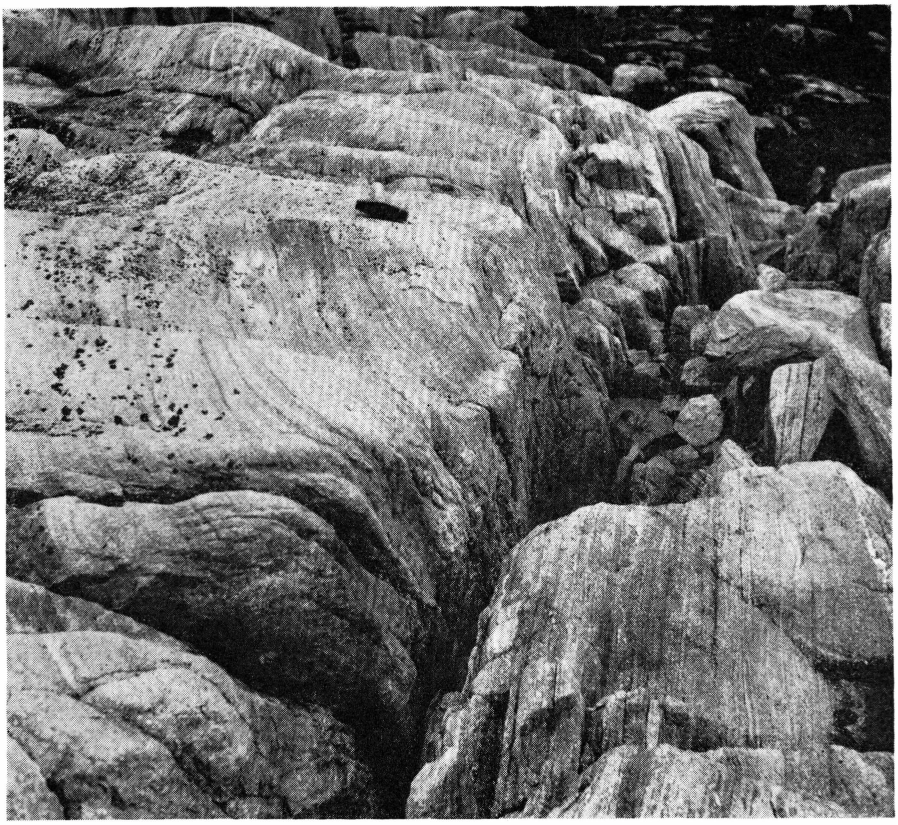

Fig. 18. An F_3 fold of concentric type in homogeneous gneiss. The fold has an almost vertical axis.

scopic structures as some sub-areas are better exposed than others: some have long stretches of ice-polished coasts which contrast with lichen-covered inland areas. Thus the number of measurements in the stereographic diagrams reflects the non-uniformity of exposure throughout the area as well as the degree of development of the macroscopic structures.

First Phase Structures

As F_1 folds only occur on a mesoscopic scale and as too few measurements of F_1 structures were able to be made reliably on the planar coastal exposures, little discussion of F_1 fold structures is worth while at this point.

The most penetrative S-plane of the area is S_1 which is defined on a macroscopic scale by the boundaries between the lithological horizons seen on the geological map. Where unaffected by the second and third

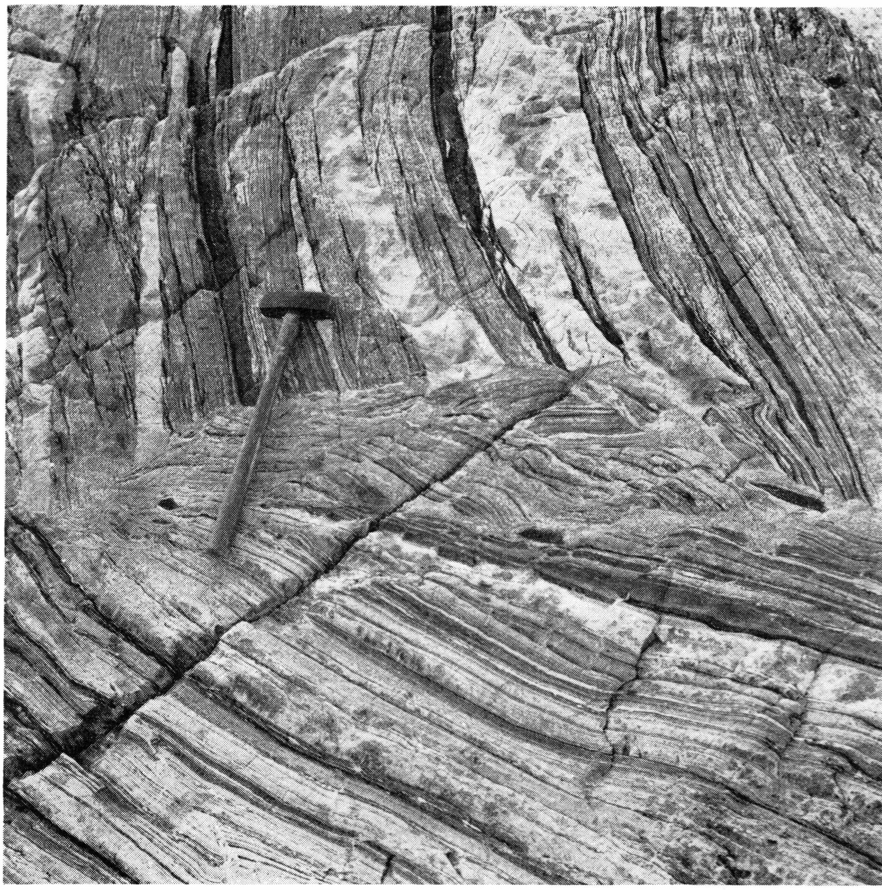

Fig. 19. Tectonic mélange of F_3 age in banded gneiss on Inuarutdligaq island in the neighbouring Sydprøven area. Slip ceased to take place along S_1, relief being expressed by the disruption of the foliation. Photo: G.G.U., D. BRIDGWATER.

phases of folding, this macroscopic S_1 has a NE-SW strike, as along Sangmissoq fjord. This original attitude of S_1 is reflected in subarea 19 by the strong maximum of poles to S_1 planes dipping steeply to the NW.

In the vicinity of Sangmissoq fjord there are two successions of ten gneiss horizons. Four horizons of veined gneiss alternate with five of homogeneous gneiss and these are followed by a banded gneiss horizon. Except for a thin centrally-situated veined gneiss horizon it is significant that the two successions are identical, only the order is reversed: even the widths of individual horizons are the same throughout. Thus there appear to be two successions which are repeated. The significance of this repetition with respect to the first phase structures is discussed on p. 38.

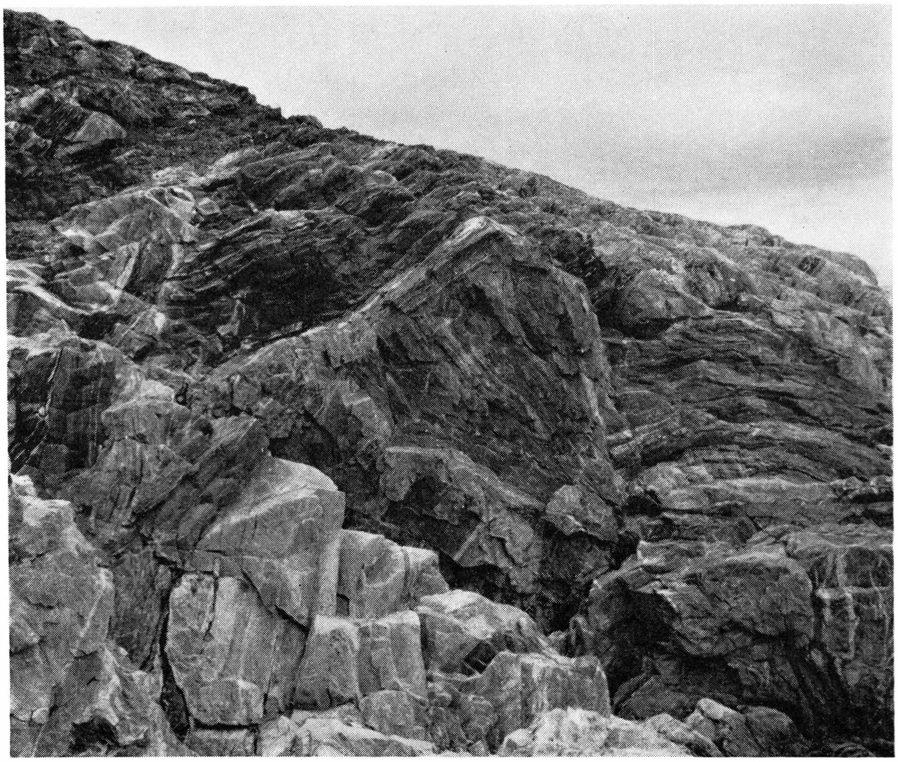

Fig. 20. Tectonic mélange formed during the third phase movements on Inuarutdligaq island in the neighbouring Sydprøven area. Between the angular blocks there is heavily sheared gneiss. Photo. G.G.U., D. Bridgwater.

Second Phase Structures

The form of several macroscopic second phase folds is seen on plate 2 and illustrated in the S_1-pole diagrams of plate 3. Where unaffected by third phase folds F_2 folds plunge shallowly to the NE or SW. There are two principal macroscopic F_2 folds—the West Kangeq and Sârdloq folds—the distance between which is 7.5 km.

On West Kangeq there is a major antiform in banded gneiss. Sub-area 20 shows that the fold plunges shallowly to the SW and measured fold axes are roughly coincident with βS_1. This antiform continues through the outer islands to the west-Ũmánalik and Ũmánaq, the βS_1 of sub-areas 21 and 22 being coincident with that of 20. Although being homoaxial, sub-areas 20, 21 and 22 have been left as separate diagrams as they have different point concentrations. The antiform does not continue to the east of Kangeq; sub-area 18 shows that S_1 dips steeply to the NW and SE varying only slightly from vertical.

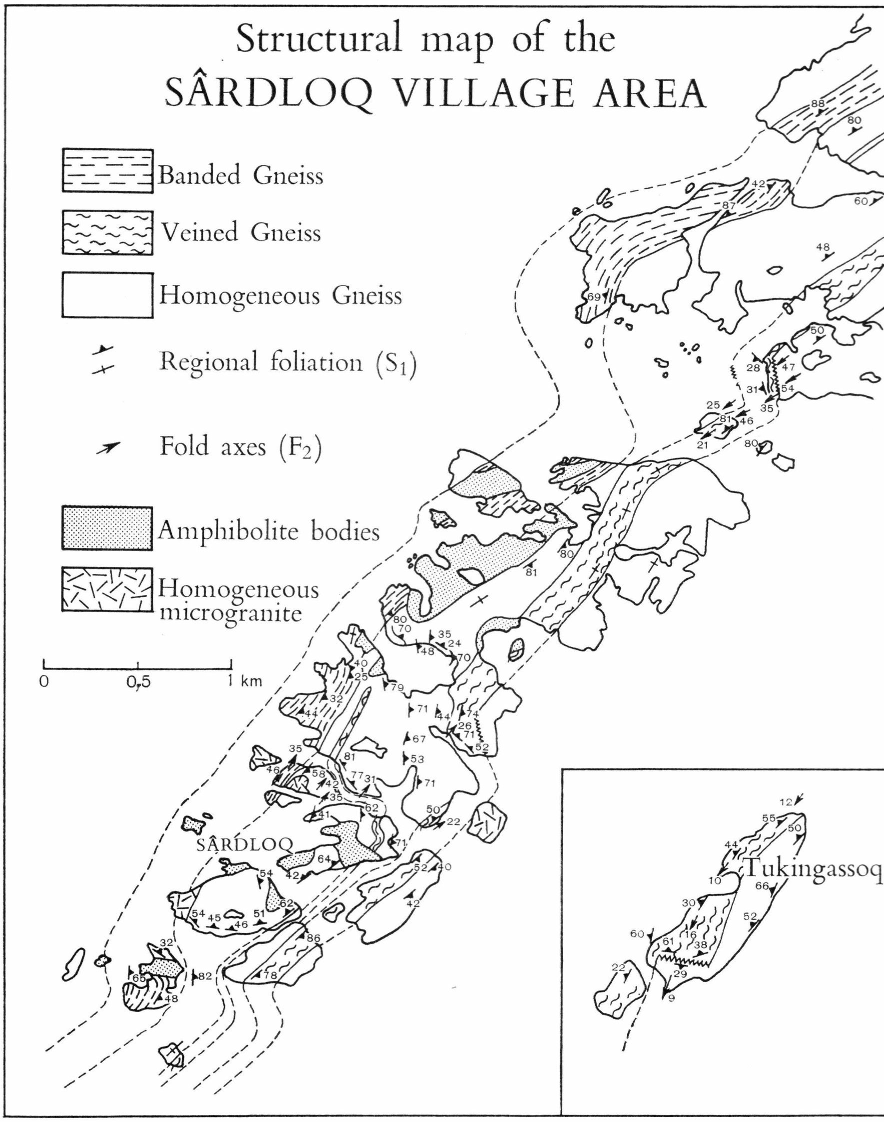

Fig. 21. Structural map of the Sârdloq village area showing intercalated horizons of veined, banded and homogeneous gneiss. The horizons are folded by macroscopic F_2 folds which indicate by their sense of vergence a synform to their east. In the inset is seen a structural map of Tukingassoq island on which F_2 folds indicate by their vergence direction a synform to their west. These two groups of folds demonstrate the presence of a major synformal closure not far south of Sârdloq village.

In the vicinity of Sârdloq village there is a series of major asymmetrical F_2 folds (fig. 21) the short limbs of which range from 300–700 m in length from closure to closure. By their consistent sense of vergence these folds indicate the presence of a major synformal closure to their

SE. The long limbs are vertical or dip to the SE, while the short limbs dip shallowly to the NE or SW giving rise to "flat belts" which are an unusual feature of the area. In the hinge zone of the folds i. e. on the short limbs the veined gneiss is extremely highly folded, the banded gneiss is moderately folded but the homogeneous gneiss exhibits very little minor folding. Sub-area 26 has a diffuse but pronounced S-pole girdle, and sub-area 27 has a pronounced girdle, the axes of which plunge shallowly to the NE approximately coincident with the measured axes of minor folds. The S-pole girdle of sub-area 25 has an axis plunging shallowly to the SW.

On Tukingassoq island in sub-area 28 there is an asymmetrical F_2 fold which is about 300 m from closure to closure along the short limb (see inset of fig. 21). By its sense of vergence this fold indicates the presence of a major synformal closure to its south-west. The long limbs dip to the NW and the short limb to the SW as is shown by the girdle in sub-area 28. This stereographic plot also has a girdle the axis of which plunges steeply WNW which reflects the strike swing on Ũmánarssuaq island which is of F_3 age.

Apart from an F_3 girdle sub-area 30 has a weak F_2 girdle and sub-area 31 a strong F_2 girdle showing the presence of second phase folds which plunge to the E and NE respectively.

In the north-east of the area where the third phase folds are predominate, there is local evidence of second phase folding as shown by sub-areas 6, 10 and 12, in which βS_1 plunges shallowly to the NE or SW. Sub-areas 1 and 4 have weak equant maxima.

The constructed β axes within the different sub-areas have been compiled to form synoptic diagrams representative as tectonic diagrams for the whole area. Fig. 22 is a synoptic diagram of constructed βS_1 axes. It can be seen that they plunge shallowly to the NE and SW and that the synoptic S_2 surface for the whole area strikes NE-SW with a vertical dip i. e. the βS_1 lie on a vertical great circle girdle. This synoptic picture of the second deformation phase accords with the observed F_2 minor folds which have NE-SW trending axes and approximately vertical axial planes.

It can be seen from fig. 22 that some β axes plunge to the east. These have been folded from their original NE-SW trend into this position by the third phase folds. As F_3 are concentric folds the β axes have been rotated on small circles of the stereographic projection. The mechanism of this type of superposition by flexural slip folding has been described by Weiss (1959, p. 92) and Ramsay (1960).

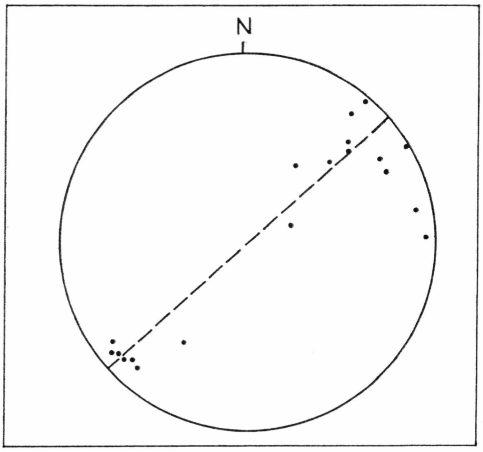

Fig. 22. Synoptic diagram of constructed β axes for F_2 folds from all sub-areas. The axes fall on a great circle girdle representing the macroscopic S_2 for the area: this strikes NE-SW and has a vertical dip.

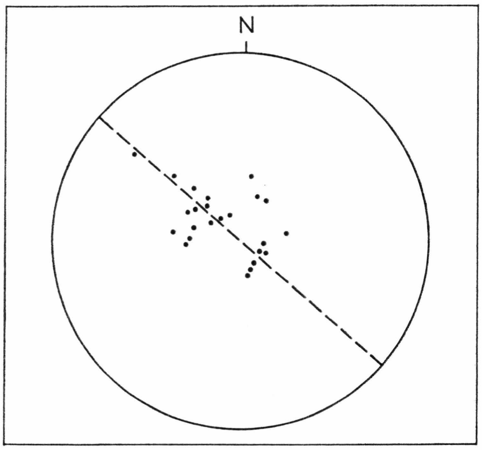

Fig. 23. Synoptic diagram of constructed β axes for F_3 folds from all sub-areas. The axes describe a diffuse great circle girdle with a horizontal axis. The girdle coincides with the macroscopic S_3 for the area which has a NW-SE strike and vertical dip.

Third Phase Structures

Mesoscopic F_3 folds are rare in the Sârdloq area and thus it is largely on a macroscopic scale that the presence of third phase structures can be deduced. Macroscopic F_3 folds are developed mostly in the north-east of the area; their wavelength varies between 2.7–7.5 km.

The principal effect of the F_3 folding has been to deflect S_1 from its NE-SW orientation either to a N-S attitude as on Ivnarssûp qâva (sub-area 9) or to an E-W attitude as on Sánerut island (sub-area 16). Sub-area 15 connects the above two sub-areas and has a βS_1 with a steep plunge to the NW and SE. In all sub-areas in which the F_3 folding is predominant βS_1 plunges to the SE or NW. In sub-area 2 there is a shallow plunge to the NW and in sub-areas 3, 7, 9 and 14 the plunge is steep to the NW or SE.

Fig. 23 is a synoptic diagram of βS_1 axes from all sub-areas in which the third phase folding is apparent. The axes have a diffuse scatter but there are general maxima plunging steeply to the NW and SE with a shallowing of plunge towards the NW. A great circle girdle with a horizontal axis has been added to the diagram defining the attitude of a NW-SE trending S_3 axial surface for the area.

There is no S_3 cleavage parallel to the axial surfaces of the F_3 mesoscopic folds. From a stereometric point of view the macroscopic S_3 is the only statistically planar surface in the area, as there has been no later superimposed deformation. The macroscopic S_3 surfaces are vertical planes striking NW-SE.

The present foliation pattern of the area is determined as much by the concentric F_3 folds as by the similar F_2 folds, the macroscopic S_3 surfaces being approximately normal to the NE-SW attitude of S_1 and S_2. The superimposition of the third folds on the major F_2 folds satisfactorily accounts for the total outcrop pattern of the regional foliation.

To summarise, the sub-area diagrams can be divided into three types:

1. Sub-areas in which only second phase folds are present e. g. 20, 21, 25, 26 and 27.
2. Sub-areas in which both second and third phase folds are present e. g. 28, 30 and 32.
3. Sub-areas in which only third phase folds are present e. g. 2, 9, 14 and 15.

iii) Microscopic Scale

S_1 Porphyroblastesis

Feldspar porphyroblasts, reaching 4 cm in length, have a structural significance as they define by their planar dimensional orientation the plane of the foliation, S_1, of the homogeneous gneisses. In the veined and banded gneisses their orientation accentuates the S_1 banding.

Both plagioclase (oligoclase) and microcline (mostly non-perthitic) form porphyroblasts. In places they are in roughly equal proportions in individual layers, but often plagioclase predominates and to such an extent that some layers contain only plagioclase prophyroblasts: these are plagioclase-rich gneisses. The microclines attain the largest grain sizes. The porphyroblasts have a sub- to euhedral form in the homogeneous gneisses but they are more augen-shaped or anhedral in the veined gneisses.

Muscovite, biotite and hornblende lie with their longest axes parallel to the walls of the porphyroblasts, so that they appear to wrap around them. Finger-like lobes extend from the porphyroblasts into and between the matrix grains, and inclusions of plagioclase, quartz, microcline and biotite tend to be more abundant in the peripheral zone of the porphyroblasts. It is clear that the formation of the porphyroblasts took place as a late feature in the build-up of the gneiss mineral assemblage, post-dating the growth of the matrix grains; it occured during a late stage in the formation of the first phase folds and the regional foliation.

F_2 Recrystallisation

Only in a few localities has an axial plane cleavage been observed in the F_2 folds. Microscopically it can be seen that parallel to the axial surfaces a new planar fabric has developed composed of alternating laminae of quartz-feldspar and biotite-hornblende. Slightly flexed micas afford the only evidence of the earlier deformed fabric.

In typical F_2 fold cores in the highly folded veined gneisses there is no evidence of movements post-dating the recrystallisation. Muscovite and biotite commonly interlock in polygonal arcs in the hinge zone (fig. 24) and mutual quartz grain boundaries are markedly planar with in places equilibrium angles of 120° at triple junctions: quartz shows little or no sign of strain. It is clear that the crystallisation in fold cores started under syn-tectonic conditions but that the effects of strain on the constituent minerals have been entirely obliterated by a continuous recrystallisation which outpaced the deformation. The present grain fabric is a result of syn- to post-tectonic recrystallisation with respect to the second fold movements.

F_3 Retrogression

In the gneisses epidote and chlorite can be seen to replace hornblende and biotite and to cross-cut the regional foliation defined by these minerals. In the tectonic mélange, believed to be of F_3 age, epidote and chlorite occur in the sheared gneiss between the rotated blocks. Although there are no definite criteria to relate the growth of late epidote and chlorite with the third phase folds, as these mostly occur on a macroscopic scale, it is considered most likely that this retrogressive crystallisation was associated with the last fold movements which took place under relatively brittle conditions.

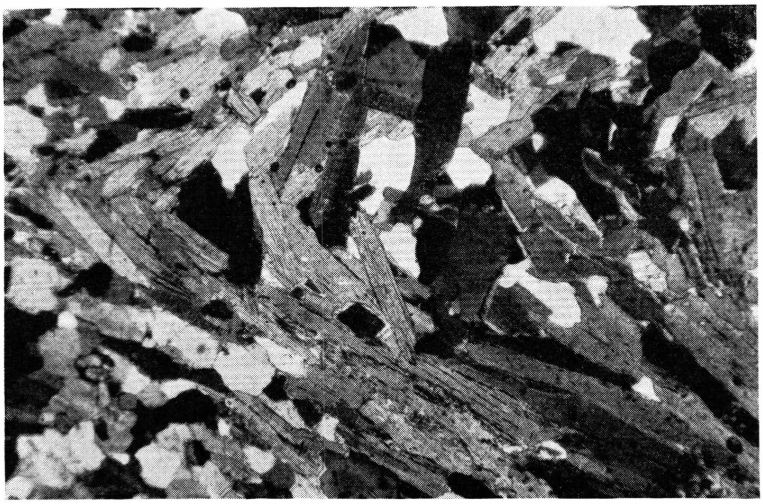

Fig. 24. Photomicrograph of an F_2 fold core in veined gneiss. Biotite crystals interlock in polygonal arcs in the hinge zone of the fold indicating post-kinematic crystallisation with respect to F_2. × 27.

Interpretation

First Phase Structures

It should be noted that the first observable folds in the area cannot be confused with partly transposed F_2 folds in which S_2 axial surfaces partly truncate S_1 in the hinge of the folds, because the F_2 folds formed during a plastic stage of deformation when axial slip movements rarely formed in fold hinge zones. Moreover, the presence of F_1 closures refolded by F_2 folds (fig. 13) clearly establishes the existence of minor folds before the formation of F_2.

On cursory examination it might be considered that the S_1 foliation represents the first structural plane of the area having formed by recrystallisation of the bedding of a supracrustal series giving rise to the succession of lithological horizons. However, the presence of the intrafolial folds indicates that there was a period of folding either prior to or contemporaneous with the formation of S_1.

As stated by Turner and Weiss, 1963, p 17: "the presence of intrafolial folds is one of the criteria of transposition of S-surfaces". It was Sander (1930) who termed tectonically derived foliation a transposition foliation (Umfaltungsclivage). The presence of a partially developed foliation and of partially obliterated fold cores is a common feature of metasedimentary rocks belonging to the superstructure. Bowes and Jones (1958) have described an excellent example of the progressive development of the transposition of bedding in the Dalradian rocks of Scotland with preservation of relict fold closures in the derived tectonic foliation. Even in metasedimentary rocks it may not always be possible to relate isolated intrafolial folds with a major fold structure. De Romer (1961) met this problem in his study of the Appalachian rocks of SE Quebec.

The presence of boudinage structures in conformable replacement pegmatites and of folded cross-cutting veins indicates that flattening has taken place in association with the formation of the regional foliation. This foliation, S_1, was formed during a process of granitisation under P/T conditions corresponding to the amphibolite facies and thus it can be expected that flattening took place during the formation of S_1 at this infrastructural level. If the intrafolial folds were initiated in a pre-migmatitic metasedimentary stage, it is easy to envisage that they became progressively obliterated during the granitisation by a process of transposition and flattening.

There are two possibilities concerning the origin of the Sârdloq intrafolial folds:

a) They may be the minor parasitic folds of a large pre-migmatitic isoclinal fold. Evidence in favour of this mode of formation is afforded by the repeated succession of lithological horizons which can be traced for a considerable distance along their strike. According to this theory S_1 is the granitised axial surface of the early isoclines and an essential prerequisite to the theory is that the original folds were entirely isoclinal, so that the axial plane foliation in the form of S_1 developed parallel to the boundaries of the lithological horizons. By a process of transposition in accompaniment with granitisation the parasitic folds are gradually destroyed and if these processes go almost to completion, only a few tight to isoclinal fold hinges may survive.

A simple alternative to this theory is that the closure of the pre-migmatitic isocline was removed by a slide along the axial plane during granitisation.

Although there is a small possibility that either of the above two interpretations is applicable to the Sârdloq rocks, it is considered that with the available evidence it would only be supposition to conclude the earlier existence of a large-scale pre-migmatitic structure. Weiss (1958, p 14) in fact has pointed out the danger of making such an assumption without sufficient information. The repeated succession previously described is more likely the result of a chance combination of horizons within a rapidly alternating stratigraphic succession.

It is significant that the presence of isoclinal major pre-S_1 folds has not been detected by any GGU geologists in any areas belonging to the Ketilidian fold belt, and in particular not even in the weakly migmatised

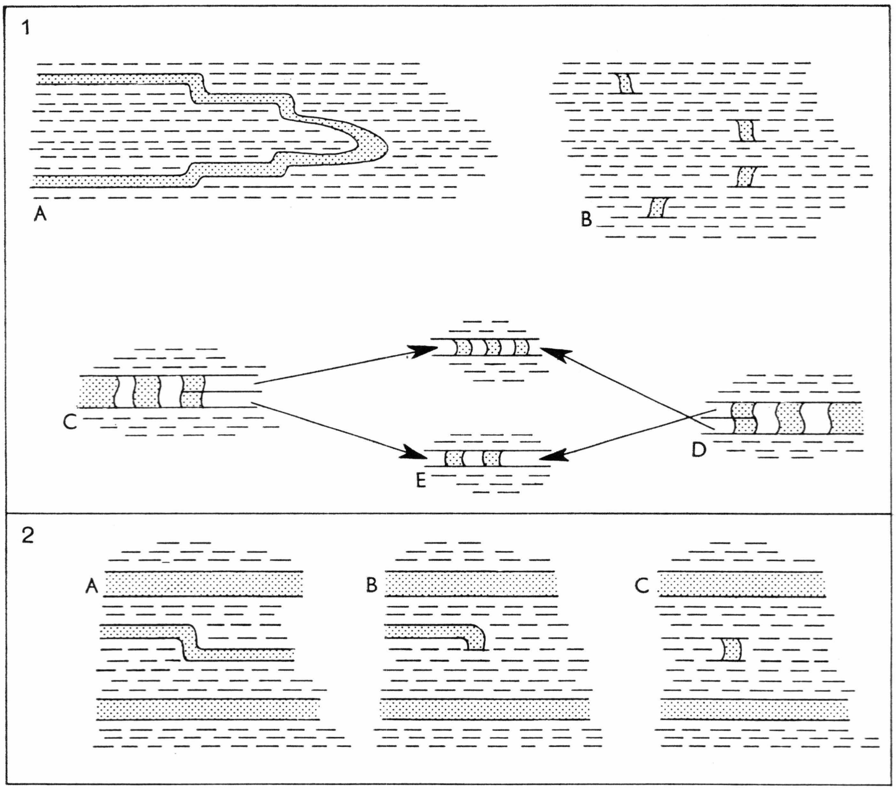

Fig. 25. Diagrammatic representation of two ideal modes of formation of intrafolial folds in gneissic rocks. In 1 A a strong cleavage, S_1, has developed along the axial plane of an isoclinal fold. This may take place in a metasedimentary stage. Further development of the cleavage into a regional foliation (S_1) in accompaniment with granitisation leaves relicts of the parasitic folds, the full sense of vergence of which can still be seen (1 B). At this stage the position of the primary fold closure can still be discerned. However, with further obliteration the intrafolial folds pass from stages C and D to E, in which only single closures are preserved. No longer can the presence of the primary structure be discerned at this stage and indeed should not be inferred from such fold relicts. In 2 A a drag fold has formed in an incompetent layer situated between two competent undeformed layers. By a process of tectonic thinning and planar slip during granitisation the fold may be progressively destroyed (2 B) until only a single fold closure is preserved (2 C).

rocks at a higher level just below the migmatite front or in the supracrustal rocks of the superstructure. It is concluded therefore that there is no evidence to suggest that the Sârdloq intrafolial folds originally belonged to a major pre-S_1 isoclinal structure.

As it is possible that some intrafolial folds exist in other areas in a less advanced stage of obliteration, some remarks will be made concerning their recognition. Progressive stages in the formation of intrafolial folds from an earlier large-scale fold by a process of axial plane granitisation are shown diagrammatically in example 1 of fig. 25. If the folds have only reached the stage of obliteration shown in 1 B, their sense of vergence can still be discerned and therefore it is possible to determine the position of the earlier primary fold closure. If these folds undergo a more advanced stage of obliteration, only single fold hinges are preserved as seen in 1 E, in which case the attitude of the primary fold can no longer be detected. At this stage conclusions concerning the existence of earlier major folds should remain a matter of conjecture.

b) The Sârdloq intrafolial folds may have formed originally as drag folds along the contacts of or parallel to planes within the lithological horizons. The drag folds could have been caused by early slip movements due to competency differences between horizons probably in a metasedimentary stage prior to or in association with the syn-S_1 granitisation. The progressive stages in the destruction of such drag folds during the formation of a granitic regional foliation are shown diagrammatically in 2 of fig. 25. On the available evidence it is suggested that this second possibility is the more likely for the formation of the Sârdloq F_1 folds.

Second Phase Structures

In the Sârdloq area there are only two major second phase folds observed on a macroscopic scale:

1) The West Kangeq antiform, the axis of which plunges shallowly to the SW (sub-areas 20 and 21).

2) The Sârdloq synform, the closure of which is covered by water not far to the south of Sârdloq village. Evidence of this synformal structure is given by the series of macroscopic, asymmetrical folds near Sârdloq village (fig. 21) which indicate by their vergence a synform to their east, in combination with the macroscopic asymmetrical fold on Tukingassoq which indicates by its vergence a synform to its west. The presence of this major synformal closure is expressed by the marked large-scale strike convergence towards the SW corner of the area. The widespread banded gneisses of West Kangeq on the northern limb of the fold correspond to the equally widespread banded gneisses of the N Ũmánartût island group on the southern limb. Sub-areas 25, 26, 27 and 28 demonstrate that the axes of the parasitic folds plunge shallowly to the SW and NE coincident with the βS_1 of the major structures demonstrating that the major and minor folds are broadly coeval. The axis of the major fold probably has a similar

plunge in either or both directions. The West Kangeq antiform and the Sârdloq synform are complementary F_2 folds developed contemporaneously in response to the same stress system.

On a mesoscopic scale there are only rare examples of F_2 folds visibly refolding F_1 folds (fig. 13). Besides other criteria these satisfactorily establish the age relations between the first and second fold phases.

During F_2 times there was a strong lithological control of folding, as the thin veined gneiss horizons acted as incompetent units in the succession. Principal fold movements took place in these horizons with formation of abundant parasitic folds, in contrast to the banded gneiss horizons in which relatively few folds developed. The homogeneous gneiss behaved competently during the fold movements and probably deformed more by a process of flattening, on account of the fact that it is the most homogeneous of the three gneisses with no lithological layering (according to English terminology this is a foliated granite). An essential prerequisite for the formation of folds is the presence of a planar parallel fabric or laminar structure on which slip can take place enabling initial concentric folds to form.

F_2 minor folds are characterised by a "similar" style in which movement of material has ideally taken place along planes parallel to the fold axial surfaces giving rise to attenuated limbs and thickened hinges. A second characteristic of the F_2 folds is the presence of arrowhead structures which are the result of an advanced development of similar folds indicative of an extreme state of plasticity and mobility of material in the rock series. A third feature common to this type of tectonite is the presence of curviplanar axial surfaces which are highly developed in the Sârdloq veined gneisses (figs. 10 and 11). Such structures formed by long-lasting continuous deformation acting on material in a plastico-viscous state. Combination of the above three features results in what is commonly termed a plastic style of folding, a style which suggests a high degree of fluidity in the rock series. The presence of abundant biotite, muscovite and hornblende in the Sârdloq veined gneisses is indicative of a high water pressure, reflecting an original high pore pressure in the rocks which is the fundamental cause of such plastic style of folding, also frequently observed in glacier-deformed Quaternary deposits and termed by some "wild-folding". That the folding of the structures under discussion was not wild is shown by the consistent direction of trend and amount of plunge of fold axes irrespective of the highly variable disposition of associated axial surfaces (see also Berthelsen, Bondesen and Jensen (1962)). An extreme development of this type of deformation is represented by refolded isoclines, all axes of which are mutually coincident (fig. 12). It is clear that the kinematic c axes remained in the ac plane during a single continuous deformation phase and that the rotational component played a major role in the formation of these folds.

The presence of conjugate folds in the plastically deformed veined gneisses is interesting from the rheological standpoint as Ramsay (1962a, p 525) has concluded that "conjugate folds ...... are characteristic of rock deformation under brittle conditions". There can be no doubt that the conjugate folds of the Sârdloq area formed under plastic conditions, as they are intimately associated with flowage, similar-type folds and the axes of all these folds are parallel. Moreover, it is certain that the F_2 folds formed under synmigmatisation conditions. Hills (1963, p 467) has also pointed out that conjugate folds may form under plastic conditions of deformation and that Nadai (1931) was one of the first to recognise that such structures may be the result of plastic deformation of geological material. It appears that conjugate folds may form in two environments—under plastic (syn-migmatisation) conditions and late brittle conditions of rock deformation.

It has been shown (figs. 2 and 14) that the granitic neosome passes along the axial planes of some F_2 folds, which indicates that the period of migmatisation was syn-tectonic with respect to the second fold movements. The plastic style of folding and the water-rich condition of the rocks can be ascribed to a period of deformation that took place synchronously with migmatisation. In the hinge zone of F_2 folds (fig. 24) micas form polygonal arcs and quartz-grain boundaries are commonly planar with 120° junctions at triple points indicating crystallisation under equilibrium conditions in a stress-free environment (Voll, 1960): both features demonstrate that the crystallisation outlasted the second fold movements. Most of the fold features described above are from the heavily folded veined gneiss horizons.

An S_2 axial plane cleavage occurs in a few places in the area. This has the form of a strain-slip cleavage in micaceous layers and a fracture cleavage in competent banded gneiss. There is also a porphyroblastic mineral orientation in suitable horizons. The F_2 recrystallisation took place under P/T conditions corresponding to the amphibolite facies. An S_2 is rarely developed because the crystallisation was synchronous with the deformation, and it outlasted the fold movements to such an extent that a homogeneous growth fabric developed in the granitic layers. This type of syngenetic deformation/crystallisation fabric is common to the migmatitic gneisses of the Precambrian infrastructure where an axial plane cleavage is a rare phenomenon in contrast to the lower grade non-migmatised rocks of the superstructure where it is highly developed.

The geometry of the F_2 axes will now be considered where they have not been affected by the third phase of folding. The F_2 minor fold axes plunge in different sub-areas either to the NE or SW. This is illustrated by subareas 25 and 26 which have pronounced S_1 pole girdles, the axes of which (βS1) plunge in these directions coincident with measured F_2 minor fold axes. Locally minor folds can be seen to plunge in opposite directions every few metres. In only one locality (within sub-area 26) have F_2 axes been seen to plunge to the NW i. e. across the regional trend. The variable plunge (NE and SW) implies two possibilities:

a) There was a single non-plane tricline deformation (or two synchronous deformations with higher symmetry in which the ac planes were mutually perpendicular).

b) The fabric was produced by two superposed unrelated strains.

The significance of these alternatives has been discussed by WEISS (1958, p 28–32) and the two types of structures were termed respectively B⊥B and B∧B by SANDER (1948, p 73–83 and 150). According to SANDER (op. cit., p 180) the two types can be distinguished by the angle between the two sets of fold axes. If the axes are mutually oblique, it can be concluded that the folds resulted from superposed unrelated biaxial strains. However, WEISS (1958, p 33) has shown that this angular relationship does not hold in the particular case where the two kinematic c axes are mutually perpendicular. In the Sârdloq veined gneisses a complementary set of F_2 axes is generally absent, which may suggest that the variability in plunge resulted from a single non-plane tricline deformation of the B⊥B type. This triclinic stress system operated on a macroscopic scale, but on a mesoscopic scale the deforming stresses had orthorhombic symmetry, as has been demonstrated from the conjugate folds.

Consideration of the geometry of F_2 structures where they have been refolded by F_3 folds will be postponed to the immediately following section.

Third Phase Structures

F_3 folds mostly occur on a macroscopic scale. Axial plunge varies from steep (sub-areas 9 and 16) to shallow (sub-area 2) to the NW; some dips are overturned, thus the axes plunge steeply to the SE (sub-areas 9 and 15). The variable plunge is due to the fact that the F_3 folds are situated on the limbs of the F_2 structures i. e. F_3 was superimposed on an already folded S-surface. F_3 folds are concentric in style showing that they formed by flexural slip on S_1. An S_3 axial structure is not developed, as the formation of the third phase folds took place under post-migmatisation and late-metamorphic conditions in the Sârdloq area.

A tectonic mélange developed locally probably in response to the third phase movements. Alternatively it is possible that the mélange was formed during the F_4 phase of folding, which in the Nanortalik area was associated with faulting. This F_4 is equivalent to the F_3 of Escher (1966), (see table 1). The mélange was formed in a relatively brittle stage of deformation when S_1 had ceased to be the movement plane in the generation of the F_3 folds. Instead of taking place as folding, relief of compression expressed itself by sliding and thrusting, resulting in the disruption of S_1 so that the rocks were segmented into disoriented blocks (figs. 19 and 20).

Recrystallisation took place locally between some blocks with formation of epidote and chlorite. The formation of the mélange was apparently lithologically controlled, as on Inuarutdligaq island disruption took place within a 50 m horizon of banded gneiss which can be followed for half a kilometre. The formation of the mélange under brittle conditions agrees well with the concentric style of the third phase folding which took place under epidote amphibolite facies conditions.

A diagrammatic structural stereogram is shown in fig. 26 illustrating the generalised structure of the Sârdloq area resulting from the superposition of the F_3 on the F_2 folds.

Summary of structural development in relation to migmatisation and metamorphism

During the formation of the three phases of folding there were varying degrees of repeated migmatisation and metamorphism.

The first observable folds (F_1), probably initiated during a premigmatitic stage, occur now as rare intrafolial folds seen only on a mesoscopic scale. During the formation of S_1, the regional foliation, there was metamorphism under amphibolite facies conditions associated with an intense gneissification which transformed all earlier (supracrustal?) rocks into a series of gneisses. Although no relicts of pregneissic rocks occur, a lithological succession of alternating gneiss horizons is probably the reflection of an original supracrustal succession. Migmatisation was apparently not able to blurr and obliterate the earlier compositional differences between lithological horizons.

The second period of folding, F_2, took place under synmigmatitic amphibolite facies conditions, the granitic neosome penetrating along the axial planes of some folds. The rocks were deformed in a plastic manner; asymmetrical, similar, disharmonic folds with curviplanar axial surfaces are common. There was a strong lithological control during this phase of folding, as the majority of mesoscopic folds formed in the

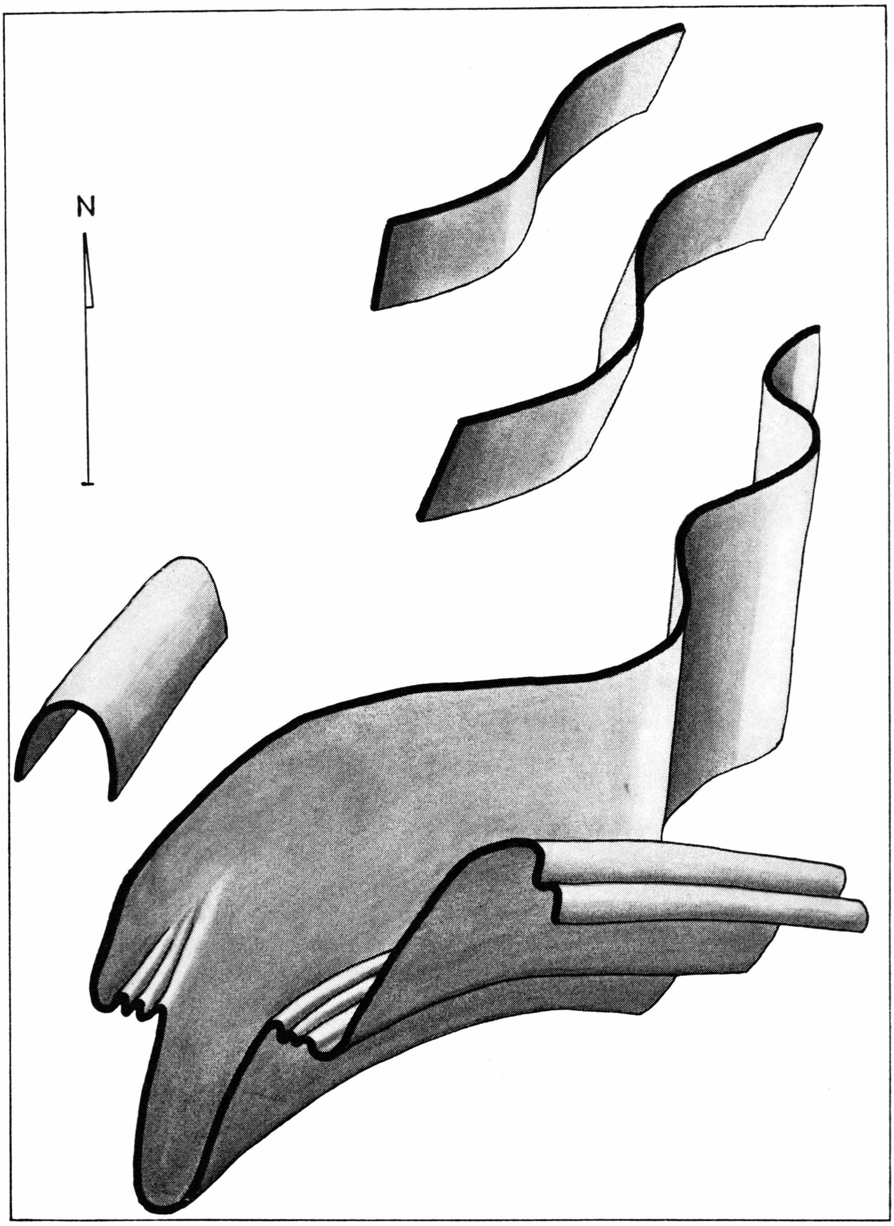

Fig. 26. Diagrammatic stereogram of the structure of the Sârdloq area formed by folding of a major F_2 synform, the axis of which plunges shallowly NE-SW, by F_3 folds with variably plunging axes trending NW-SE.

incompetent veined gneiss horizons, a few in the banded gneisses, but they rarely formed in the competent homogeneous gneisses which had reached a more granitic state, probably due to their original composition.

A major synform was formed during the F_2 folding, the closure of which is now covered by water. Growth of mica in polygonal arcs and of mutual planar quartz boundaries with 120° triple junctions in F_2 fold closures are indicative of an equilibrium growth fabric developed under late- to post-tectonic conditions with respect to the second fold movements. In places in the cores of major F_2 folds there was formed a new mineral growth defined by aligned quartz and feldspar individuals, representing a local syn-F_2 porphyroblastesis.

The third and last phase of folding, F_3, took place under post-migmatitic epidote-amphibolite facies conditions resulting in a buckling of the S_1 foliation which had an already variable attitude. F_3 folds mostly formed on a macroscopic scale around axes that have a general steep plunge to the NW and SE. The deflection of the strike from the regional, pre-F_3, NE-SW trend is a result of this last phase of folding. A tectonic mélange was locally formed by the F_3 movements demonstrating that the rocks has reached a relatively brittle state. Slip no longer took place along S_1, tectonic relief being expressed by thrusting and sliding, resulting in the disruption of the regional foliation.

IV. CORRELATIONS

In many areas surrounding the Sârdloq area, particularly to the SE, three phases of folding have been recognised by GGU geologists. An attempt will be made here to present a preliminary correlation in relation to the structures of the Sârdloq area.

The correlation of the Ketilidian fold structures is based on plate 1, compiled by the writer, showing the distribution of the axial traces of the three major fold systems south of Julianehåb. In making this correlation the possibility of the presence of locally preserved pre-Ketilidian elements has not seriously been considered. The criteria used for the correlation of the folding phases in the different areas are fold style, direction of fold trends and relationships to migmatisation. It is possible that future detailed investigations of the relations of metamorphosed basic dykes to the structures will reveal pre-Ketilidian elements in the area between Igaliko Fjord and Kap Farvel. Probably such elements will be strongly reworked so that their presence will hardly affect the interpretation of the fold pattern given in plate 1.

The fold systems observed on the map correspond to the F_2 and F_3 folds in the Sârdloq area. F_1 folds did not form major structures. It can be seen that the traces of the F_2 folds, originally trending NE-SW, have been folded, often into a N–S or E–W attitude, by the F_3 folds, the axial traces of which trend consistently NW–SE. It is apparent therefore that the second and third phases of folding have a regional distribution. The four generations of folds will be described below in respect to their variable attitude and degrees of development in different areas together with their relations to metamorphism and migmatisation.

Confusion has arisen as different generations of the four fold phases have been observed in different areas and thus have been designated by varying symbols. A tentative correlation of these fold terms is given in table 1 based on similarities in fold style and trend. It is proposed that the four phases of folding are designated F_1–F_4.

First Phase folds

S_1, the foliation in the gneisses, has a regional distribution in the infrastructural rocks throughout all the areas south of Julianehåb. This

Table 1. *Correlation of fold nomenclature by G.G.U. geologists in different areas south of Julianehåb. There are four fold phases which it is proposed are termed $F_1 - F_4$.*

	Escher (1966)	Allaart (1964)	Dawes (personal comuni-cation)	Persoz (in prep.)	Ber-rangé (1966)	Oen (personal communi-cation)	Muller (personal communi-cation)	Watter-son (personal communi-cation	Bridg-water (personal communi-cation)	Windley (this paper)	Proposed fold nomen-clature
	Nanor-talik area	Regional review	Tasiussaq area	Akulia-ruseq area	"Vatnah-verfi" area	Sermer-sôq	Peninsula between Ûnartoq and S. Sermilik fjords	"Fast-landet"	Sydprøven area	Sârdloq area	
ENE to NE trending folds locally assoc. with faulting	F_3	F_3	F_3								F_4
Variable plunge to NW or SE	F_2	F_2	F_2	F_2	F_2	F_2	F_2	F_3	F_3	F_3	F_3
Shallow plunge to NE or SW (original trend)	F_1	F_1	F_1	F_1	F_1	F_1	F_1	F_2	F_2	F_2	F_2
Intrafolial folds (NE and SW) ..			F_0					F_1	F_1	F_1	F_1

means that the dominant foliation recognised in each of the areas has a common origin i. e. the regional foliation has not undergone transposition to a new regional foliation. This has relevance both to the mode of formation of the F_1 folds which occur as intrafolial relicts within the S_1 foliation, and to the degree of development of the planar structures of the F_2 and F_3 folds which have not attained regional significance.

At this point it is convenient to speculate on the origin of the gneisses of the Sârdloq area and to correlate the macroscopic S_1 represented by the boundaries of the lithological horizons with similar structures in lower grade rocks in neighbouring areas. The succession of intercalated horizons of the three gneiss types, which can be traced for at least 30 km along the strike, most probably reflects an original succession of supracrustal rocks. The mica-rich thin incompetent veined gneiss horizons probably represent water-rich argillaceous horizons whilst the banded gneisses may have been derived from volcanic rocks. The latter is suggested by the fact that within the banded gneisses there are locally widespread amphibolitic parts which are in the process of being marginally veined by a granitic neosome. The origin of the homogeneous gneiss is more difficult to ascertain, but as it is homogeneously developed over large areas both across and along the strike, it is probable that it was derived from a supracrustal rock of widespread homogeneous composition, possibly a quartzite or greywacke.

The Sârdloq gneisses pass across the strike to the south-east through the Sydprøven area to the Akuliaruseq area where there are a few but definite remains of supracrustal rocks within the gneisses (Persoz, in prep.). Further towards the east on the peninsula between Ûnartoq and S. Sermilik fjords mapped by J. Muller the amount of supracrustal material is known to increase at the expense of the enclosing gneisses, until these rocks pass eastwards through the migmatite front into the sedimentary and volcanic rocks of the superstructure on "Fastlandet" mapped by J. Watterson. In the reverse order a progression in the transformation of supracrustal to gneissic material can probably be followed from pelites, quartzites and volcanics through pelitic schists, quartzitic gneisses with a few remains of quartzites, and granite-banded amphibolites to the Sârdloq area succession of veined gneisses, homogeneous gneisses and banded gneisses.

Immediately to the north of the Sârdloq area in Julianehåb fjord there is the island of Mato mapped by Nesbitt (1961) and Allaart (in prep.) on which there are tuffaceous rocks clearly of metavolcanic origin. These are intensely banded and further along their strike there is an horizon containing banded gneiss and other rocks which exists as an 18 km long relict within the Sanerutian-reactivated granite of the

Julianehåb peninsula. This may suggest that the Sârdloq banded gneisses are recrystallised derivatives of a volcanic series.

The intrafolial F_1 folds have been observed in most areas but it is difficult to obtain any idea of their relative abundance as they are quite rare features everywhere. It has been previously concluded that the formation of the F_1 folds probably took place in connection with that of S_1, but the exact genetic relationship between these structures cannot be discerned in the Sârdloq area because 1) there are too few F_1 folds present 2) transposition or obliteration of the folds has reached a too advanced stage and 3) the folds have been observed in too small an area. For these reasons it has not been possible to elucidate the nature of the progressive development of the folds in the area concerned. However, it is suggested that the F_1 folds may be genetically equivalent to the first observable, partly relict folds in the pelitic gneisses of the Nanortalik area mapped by Escher (personal communication). These folds occur in lower grade, less migmatised rocks not far below the migmatite front and represent an intermediate stage in the transposition of a minor fold system. Similar partly transposed F_1 folds in the neighbouring area ("Fastlandet") have been observed by Watterson (personal communication) and towards the NW in the more migmatised rocks of the Akuliaruseq area by Persoz (in prep.) and of the Sydprøven area by Bridgwater (personal communication). As has been described above there is probably a progressive increase in the degree of granitisation from the Nanortalik area towards the Sârdloq area to the NW through the two previous areas mentioned. If this is so, the progressive granitisation towards deeper structural levels might be correlated with the progressive obliteration of the F_1 folds by a process of transposition in association with flattening during the development of the regional gneissic foliation. This situation is similar to that described by Zwart (1963) from the Pyrenees where the intrafolial folds below the migmatite front decrease in number from the schists to the underlying gneisses. Zwart was able to correlate these first flat-lying infrastructural folds with early upright folds in the metasedimentary rocks of the superstructure. It has not been possible to make this correlation in South Greenland, but this provides a fruitful possibility for future more detailed structural studies in this area.

Second Phase Folds

Correlation of the F_2 and F_3 folds is easier than that of the first folds as they form macroscopic structures. They fall into two easily discernible sets, the first of which is folded by the second, the F_3 folds of the latter having rectilinear axial traces. They provide an example of simple refolding on a regional scale.

It is interesting to compare this simple pattern of Ketilidian fold superposition with the complicated interference patterns resulting from superposition of several fold systems in the pre-Ketilidian rocks of West Greenland (BERTHELSEN, 1960; WINDLEY, 1964). The interference patterns comprise abundant domes, basins and all known varieties of eye folds (RAMSAY, 1962 b) all of which are generally absent in the Ketilidian fold belt. Such structures only appear to be present in the granulite facies rocks of the Tasiussaq area mapped by DAWES (personal communication).

The F_2 folds had an original NE–SW trend, but due to the F_3 folding axial traces now have a variable trend commonly in a N–S and E–W direction. The wavelengths of major folds vary between 1–7.5 km; the amplitude is difficult to determine. The inclination of the axial planes is variable; in the Sârdloq area and on Sermersôq it is steep towards the NW, in the Akuliaruseq area it is vertical, on Amitsoq it is steep towards the SE, whilst in the Nanortalik area it is shallow towards the NW.

There are two parallel third phase folds on North "Fastlandet" which warrant special mention. According to WATTERSON (personal communication) the folding was contemporaneous with a period of migmatisation, which suggests to him that the folds are of F_2 age. However, there is a possibility that these folds are equivalent in age to the F_3 folds of the Nanortalik area (see Table 1: my nomenclature). which are synchronous with a period of local migmatisation in the form of an intense pegmatisation.

Third Phase Folds

F_3 are open, mostly macroscopic folds that deform the S_1 regional foliation and the F_2 macroscopic folds. In contrast to the variable attitude of F_2, F_3 folds have a relatively constant trend in a NW–SE direction. The axial planes are vertical throughout all areas. Fold axes vary in plunge from shallow to vertical.

Fourth Phase Folds

ESCHER (1966) has described some late folds (termed by him F_3, see table 1) with a NE–SW trend in the Nanortalik area. The folds are intimately associated with faults and have a wavelength of about 4 km. Similar folds may be present in the Tasiussaq area (DAWES, personal communication).

There is a possibility that the tectonic mélange described from the Sârdloq area and correlated there with the F_3 folds may be equivalent in age to the F_4 folds of ESCHER. The association with faults on the one hand and the features of a tectonic mélange on the other are both indicative of a disruptive origin under late brittle conditions.

In the gneisses of the Akuliaruseq area (Persoz, in prep.) there are NE-trending folds shown to be of Sanerutian age by their relation to metamorphosed 2nd period basic dykes emplaced during the Kuanitic period. It has been suggested by Allaart (1964) that the NE-trending folds of Escher, here termed F_4, are either of Sanerutian age and associated with Persoz's folds or alternatively they may be the last expression of Ketilidian folding which was followed in Sanerutian time by local NE folding of basic dykes and associated gneisses. The latter alternative is favoured by the writer.

Relation between Metamorphism, Migmatisation and Deformation

The relationships between these three features is one of the most interesting aspects of the regional development of the Ketilidian fold belt.

In the Sârdloq area the metamorphism and migmatisation began during the first folding and continued into the late stages of the second folding (NE). On the other hand in the Nanortalik area they reached their peak in the synmigmatitic third phase folding (NW) at a time when retrogressive crystallisation was taking place in the Sârdloq area. It appears, therefore, that the migmatisation and metamorphism were diachronous with respect to the deformation: this is illustrated in fig. 27. This means that they transgress the different fold phases, arriving at a later time in the south-eastern part of the region. However, it must be remembered that this is a local feature, as the main migmatisation in the areas surrounding Nanortalik i. e. "Fastlandet", Sermersôq and Tasiussaq is known to have occurred in association with the F_2 NE–SW folding similar to that in the Sârdloq area.

The metamorphic isograd defined by the upper boundary of the granulite facies transgresses the stratigraphy from the base of the pelitic gneisses near Nanortalik to within the lower part of the quartzites further to the north-east. Allaart (1964, p 18) has suggested that the discordance of the thermal front may have little metamorphic significance as the quartzites of "Fastlandet" may be highly diachronous with those of the Nanortalik area.

Escher (1966) has shown that in the Nanortalik area the boundaries between all the metamorphic fields from the greenschist to the granulite facies are mutually parallel and are themselves parallel to the stratigraphic boundaries of the metasediments. If the transgression of the stratigraphy by the upper boundary of the granulite facies does not merely reflect a sedimentary facies change, an alternative explanation is that this metamorphic boundary on a large scale is not parallel to those separating the overlying metamorphic facies. Shidô (1958, p. 213) has demonstrated such a non-parallelism of thermal surfaces from the

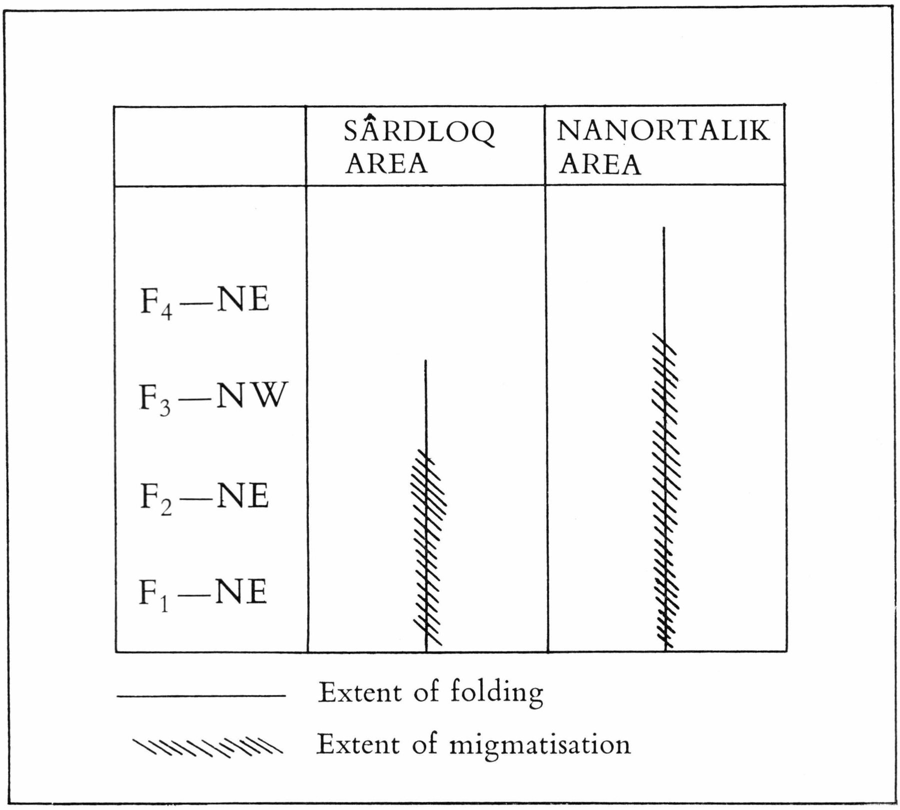

Fig. 27. Diagrammatic correlation of the extent of folding and migmatisation in the Sârdloq and Nanortalik areas. The migmatisation can be seen to be diachronous with respect to the folding reaching to a higher level in the Nanortalik area during F_3 times.

Central Abukuma Plateau region of Japan. Further detailed work needs to be done, however, in the Ketilidian fold belt of South Greenland before this relationship could be established with any certainty.

A final note on the age of the supracrustal rocks. It is as yet not known whether the supracrustal rocks lying above the migmatite front in the Sermilik fjord area are pre-Ketilidian, Ketilidian or Sanerutian in age. However, Watterson (personal communication) has pointed out that the structural correlation on plate 1 presents evidence directly bearing on this problem. It is known that the gneisses must be either of pre-Ketilidian or Ketilidian age, as the 2nd period basic dykes, which were intruded during the Kuanitic period, post-date these gneisses. As some major fold structures can be traced from the gneisses into the overlying supracrustal rocks, it follows that the latter cannot have been deposited in Sanerutian time. This limits the age of the supracrustal rocks to either pre-Ketilidian or Ketilidian.

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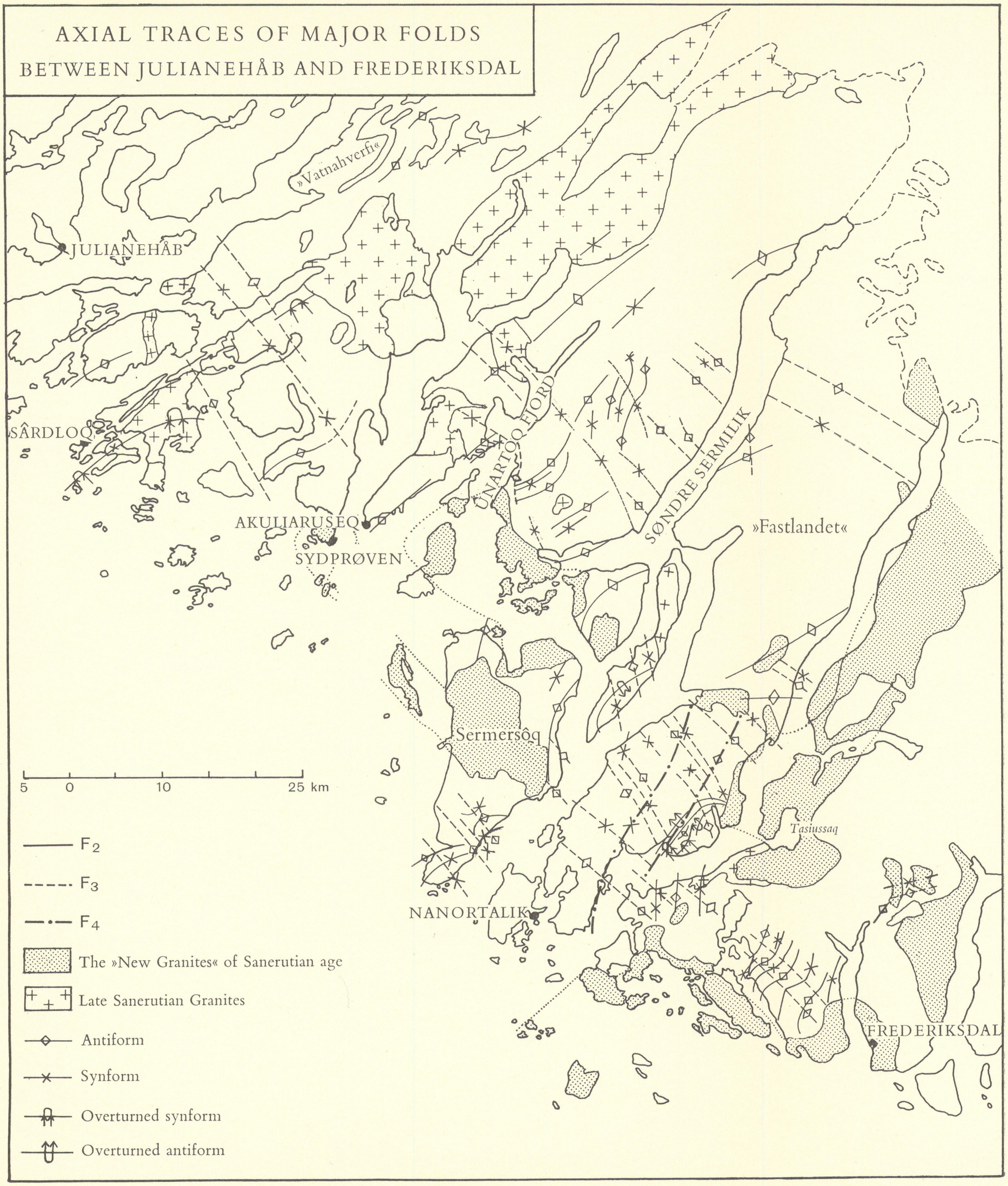
Plate 1.

Based on maps by: J. Berrangé, D. Bridgwater, P. R. Dawes, A. Escher, J. Muller, Oen Ing Soen, F. Persoz, J. Watterson, B. F. Windley.


AXIAL TRACES OF MAJOR FOLDS
BETWEEN JULIANEHÅB AND FREDERIKSDAL
»Vatnahverfi«
JULIANEHÅB
SÂRDLOQ
AKULIARUSEQ
SYDPRØVEN
ÚNARTOQ FJORD
SØNDRE SERMILIK
»Fastlandet«
Sermersôq
Tasiussaq
NANORTALIK
FREDERIKSDAL
5 0 10 25 km
F2
F3
F4
The »New Granites« of Sanerutian age
Late Sanerutian Granites
Antiform
Synform
Overturned synform
Overturned antiform