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# THE STRUCTURE AND METAMORPHISM OF MESA LAKE MAP-AREA, DISTRICT OF MACKENZIE 86 B/14 (West Half)

John V. Ross

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86 B/14 (West Half)

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By

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# PREFACE

Precambrian rocks are well exposed over vast areas of the Northwest Territories, and have been the subject of considerable reconnaissance study by the Geological Survey of Canada on broad regional lines. Such work inevitably leads to special studies such as those described in this Bulletin.

Detailed structural studies were undertaken in Mesa Lake map-area to establish the relationship of the Yellowknife and Snare Groups and to elucidate their tectonic and metamorphic history. The author has demonstrated three periods of folding, involving a complex history of metamorphism and granitic intrusion. The results are of immediate local concern in an area of considerable economic significance, and also form an important contribution to Precambrian geology.

J. M. HARRISON,
*Director, Geological Survey of Canada*

OTTAWA, September 6, 1963

BULLETIN 124 — Struktur und Metamorphismus des Kartenblatts Mesa Lake (Nordwestterritorien).

Von John V. Ross

Kurzgefasste Analyse der Struktur eines komplex gefalteten und metamorphosierten Gebiets im präkambrischen Schild. Es lassen sich drei Perioden der Faltung nachweisen, denen Blattverschiebungen folgten. In den letzten Stadien der Faltung und möglicherweise auch noch etwas später kam es zu Granitintrusionen.

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БЮЛЛЕТЕНЬ 124 — Структура и метаморфизм листа геологической карты оз. Меса, Северо-Западные Территории.

Джон В. Росс

Дается краткий анализ структуры сложно-складчатой и метаморфизованной области докембрийского щита. Установлено три отдельных периода складкообразования, за которыми последовало развитие сбросо-сдвигов со смещением вправо. Гранитные интрузии имели место во время последних стадий складкообразования или немножко позже.

# CONTENTS

## Illustrations

# THE STRUCTURE AND METAMORPHISM OF MESA LAKE MAP-AREA, DISTRICT OF MACKENZIE


## *Abstract*

Mesa Lake area is underlain by two groups of rocks: the Yellowknife Group, believed to be of Archaean age, is unconformably overlain by the Proterozoic Snare Group.

Yellowknife Group rocks comprise a monotonous sequence of graded subgreywackes and slates with one marker horizon of volcanic rocks. These rocks have been deformed into close folds that trend northeasterly with a shallow plunge to the south. Metamorphism at the time of deformation is characterized by the development of chlorite.

Snare Group rocks have at their base, a limestone, overlain by thin bedded, well-sorted sandstones and shales. Deformation of these rocks has resulted in the formation of two sets of folds that trend distinctly northeasterly and northwesterly, with shallow plunges to the southwest and northwest, respectively; the northeasterly folds are dominant and older than the northwesterly folds. This Snare deformation has also affected the underlying Yellowknife rocks, and has resulted in steeply plunging folds that are superimposed upon the limbs of the earlier Yellowknife structures. Metamorphism accompanying this Snare deformation gave rise to a widespread development of andalusite and cordierite with local sillimanite.

Bodies of white foliated microgranite were intruded during the last stages of folding. These intrusions have zones of inclusions at their margins; they had little or no thermal effect on the country rocks.

The several faults that occur within the map-area strike easterly and dip vertically, and are characterized by a right-hand tear component with some vertical displacement.



## *Résumé*

La région du lac Mesa repose sur deux groupes de roches: le groupe de Yellowknife, qui daterait de l'Archéen, est recouvert en discordance par le groupe de Snare du Protérozoïque.

Les roches du groupe de Yellowknife comprennent une succession monotone de sous-grauwackes et d'ardoises avec un horizon repère de roches volcaniques. Ces roches ont été déformées en plis serrés à direction nord–est et à faible pendage au sud. Le métamorphisme, à l'époque de la déformation, est caractérisé par l'élaboration de chlorite.

Les roches du groupe de Snare reposent sur une base de calcaire recouvert par des couches minces de grès et de schistes bien assortis. La déformation de ces roches a provoqué la formation de deux jeux de plis à direction nord–est et nord–ouest très évidente et qui présentent respectivement de légers pendages au sud–ouest et au nord–ouest. Les plis à direction nord–est sont plus nombreux et plus anciens que les plis à direction nord–ouest. Cette déformation de Snare a aussi influencé les roches Yellowknife sous-jacentes et donné naissance à des plis à pendage abrupt qui sont surimposés aux flancs des structures Yellowknife plus anciennes. Le métamorphisme qui a accompagné la déformation de Snare a occasionné la formation un peu partout d'andalousite et de cordiérite et çà et là de la sillimanite.

Des massifs de microgranite folié blanc ont fait intrusion au cours des dernières étapes de plissement. Ces intrusions présentent des zones d'inclusions à leur périphérie. Elles ont eu peu ou pas d'effet thermique sur les roches encaissantes.

Dans la région, les nombreuses failles présentent une direction est et un pendage vertical et sont caractérisées par une composante de cisaillement vers la droite avec déplacement vertical.

# INTRODUCTION

Mesa Lake map-area, which occupies about 130 square miles, lies some 180 miles north, 20 degrees west of Yellowknife. It is bounded by latitudes 64°45′ and 65°00′ and longitudes 115°15′ and 115°30′, and is within the northeastern corner of Ingray Lake map-area (Lord, 1942)[1].

Most of the map-area is north of the tree-line, with only sparse growth along the low-lying valley of Emile River. The topography is controlled largely by the structure of the underlying rocks, the highest parts of the area being underlain by hornblendic and gneissic rocks. Average elevation is about 1,300 feet above sea-level, with local relief of about 300 feet (Pl. I). Rock ridges trend parallel to the strike of the bedrock formations—which is generally in a northerly direction —the most prominent ridge in the east of the area giving rise to the name Mesa Lake. This bedrock-controlled topography has been modified to some extent by glaciation; the tops and sides of ridges tend to be rounded and the valleys between have been overdeepened.

## Previous Work

The only earlier geological work directly related to the area is that of C. S. Lord (1942) in the Snare River and Ingray Lake map-areas. He described the separation of two large groups of rocks, the Snare Group and the Yellowknife Group. Both were considered to be of Precambrian age: the Yellowknife Group was designated as Archaean; the unconformably overlying Snare Group was believed to be Late Precambrian (Lord, 1942) or Early Proterozoic (Lord, 1951).

Other works within the Yellowknife District that are indirectly related to Mesa Lake map-area are those of A. W. Jolliffe (1936), and J. F. Henderson and I. C. Brown (1950), wherein the term Yellowknife Group is defined, and the characters of its members are described and discussed.

## Acknowledgments

The author is indebted to Dr. J. C. McGlynn of the Geological Survey of Canada, who, as Resident Geologist at Yellowknife, gave much valuable help and criticism. G. H. Cluff and R. A. Alcock assisted during the field season 1958.

[1]Names and dates in parentheses refer to publications listed in the *References*.

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A. View east, from west end of Mesa Lake, along ridge underlain by metamorphosed volcanic rocks of the Yellowknife Group.

## PLATE I

B. View south, from west end of Mesa Lake, along ridge underlain by basal limestone of the Snare Group.

112720-A

# GENERAL GEOLOGY

Two major groups of rocks occur within the Mesa Lake area: the Yellowknife Group, a strongly folded assemblage of metasedimentary and metavolcanic rocks, and the overlying Snare Group, a sequence of metasediments whose structure is less complex than that of the Yellowknife Group. The author's findings, published in preliminary form in 1959, agree in general with the earlier reconnaissance mapping of Lord (1942).

Throughout the map-area, all rock exposures show evidence of deformation. The Yellowknife Group shows signs of folding along three fold trends. The first of these took place prior to deposition of the overlying Snare Group sediments and was directed along northerly trending axes having a shallow plunge to the south. After deposition of Snare Group rocks unconformably upon the Yellowknife Group, further deformation occurred such that undeformed Snare Group rocks and the already deformed Yellowknife Group were both folded along northeasterly and northwesterly trending fold axes.

Both Yellowknife and Snare Groups show signs of increasing metamorphism to the north and west. This metamorphism is believed to have been in part contemporaneous with the fold movements that deformed the rocks of both groups. Three zones of metamorphism are recognized, characterized by the presence of the index minerals chlorite-sericite, biotite-cordierite, and cordierite-sillimanite. The least altered of the lithological types are described in this section; more metamorphosed facies are described under *Metamorphism*.

In the northwestern corner of the map-area, and west of Scraper Lake, metamorphosed sediments of the Snare Group are intimately mixed with granitic material, resulting in the formation of migmatites with host rock dominant. Associated with these migmatites are large patches of coarse, foliated porphyroblastic granite. Migmatites, of metamorphosed sediments of the Yellowknife Group and granitic material, also occur in the southeastern corner of the map-area, south and east of Tropic Lake, and pass westwards into strongly foliated biotite gneiss.

Small bodies of white, foliated, tourmaline microgranite were intruded at or near the end stages of folding. These intrusions have zones of inclusions at their margins and apparently had little or no thermal effect on the country rocks. Associated with them are many simple pegmatites, some of which contain crystals of tourmaline. Other bodies of a pink, unfoliated microgranite were also intruded, probably later than the white granite. These, too, had little or no thermal effect on the country rocks and do not show marginal zones of inclusions.

Some time after the pink microgranite intrusions and the country rocks had cooled, failure by tear-faulting occurred. Several tear-faults have been mapped,



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with small lateral displacements; they strike in a northeasterly direction and dip vertically. All are characterized by a right-hand tear component with some amount of vertical displacement.

## Yellowknife Group

The Yellowknife Group is represented in this map-area by four distinct lithological types: subgreywackes, slates, hornblendic rocks, and calc-silicate granulites[1].

*Subgreywackes,* the most common rock type, are commonly associated with thin bands of slate and, more rarely, with thin bands and nodules of calc-silicate granulites. All outcrops of subgreywacke show conspicuous graded bedding, with the fine-grained lower parts of the graded units passing upwards into fine-grained slate. The graded units range in thickness from a few inches up to 20 feet, and display minute current bedding in the coarser fraction towards the base of the units. These sedimentary structures were observed throughout the map-area and thus added certainty to the stratigraphic sequence.

Most of the subgreywackes are well foliated, with their micas aligned parallel to the axial planes of local folds. Lineations, too, are well developed, often evidenced by intersection of axial-plane cleavage and bedding and by crinkling on the bedding surfaces.

These rocks are light buff to greenish grey, and vary in grain size, individual grains never being larger than 1 mm. The rocks are named subgreywacke (as defined by Pettijohn, 1949) on the basis of thin-section examination, which shows them to consist essentially of quartz, feldspar, sericite, and chlorite, with rock fragments totally absent. Feldspar comprises less than 10 per cent of the whole and, together with quartz, occurs as subrounded grains set in a matrix of chlorite and sericite flakes, which make up about 30 per cent of the rock.

*Slates* are phyllitic, greyish black to black on both the fresh and weathered surfaces, with bedding shown by slight variations of these colours. These rocks always possess a well-developed cleavage, whose intersection with the bedding planes produces a marked lineation. Slates occur with the subgreywackes as fine-grained tops of graded units. They exhibit slight variations in grain size owing to uneven grading from coarse to fine material, and also commonly show channelling and current bedding. In thin section the slates are seen to be composed of the same minerals as those that constitute the subgreywackes, but in markedly different proportions. Sericite and chlorite constitute about 75 per cent of the rock, the remainder being quartz and feldspar.

*Calc-silicate granulites* occur as isolated nodules up to a foot across that are rich in calc-silicate minerals. These nodules are developed sporadically throughout the subgreywackes and are concentrically zoned, commonly having a dark green margin with a grey-green interior.

[1]The term granulite as used in this report refers to the texture of the rocks and has no metamorphic facies connotation unless so qualified.

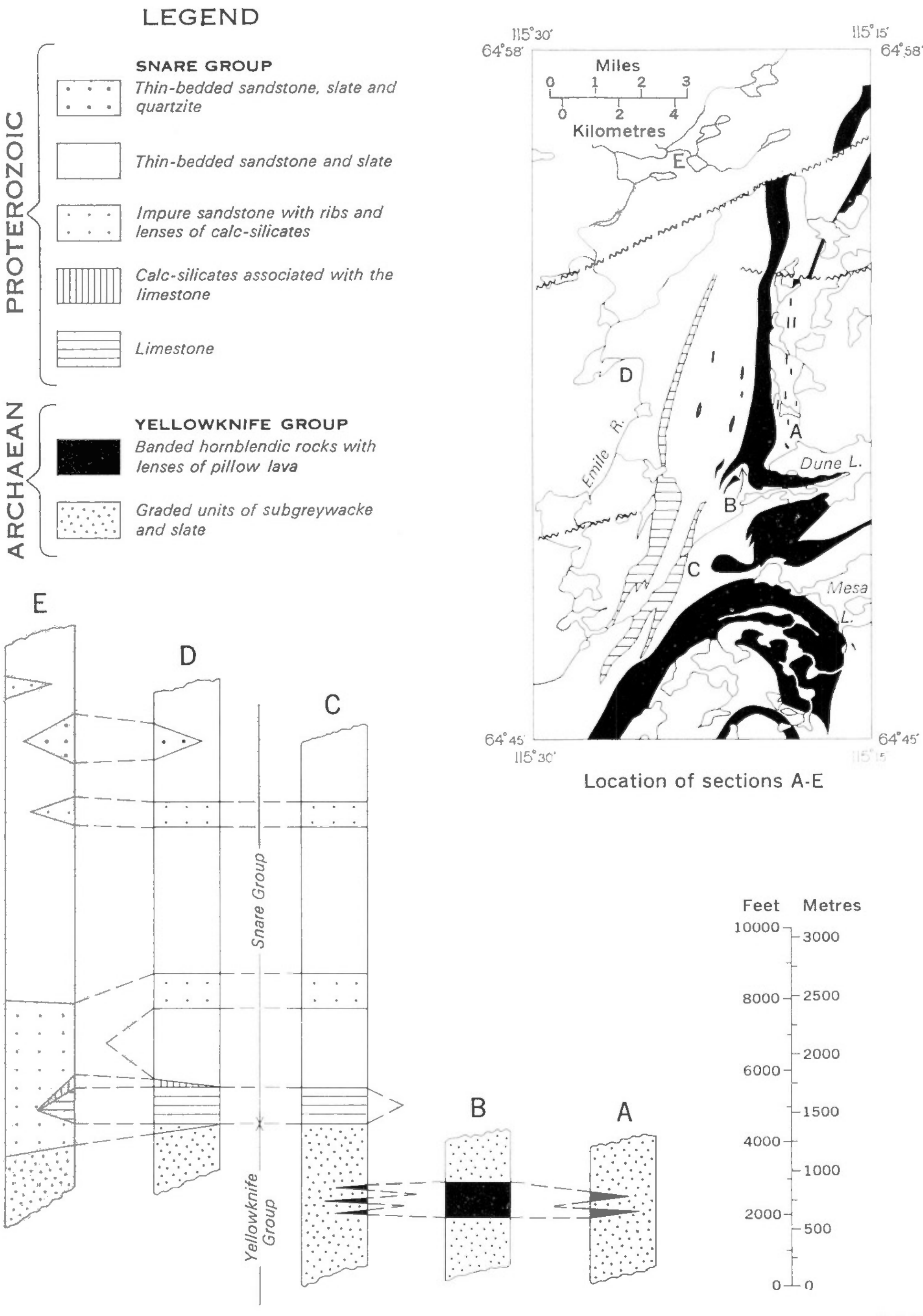


FIGURE 1. Columnar sections illustrating variations of the sediments, Yellowknife and Snare Groups.

*Hornblendic rocks,* which form a distinctive rock unit within the Yellowknife Group, include three rock types: fine-grained massive hornblendic rock, striped hornblendic rock, and hornblendic rock showing pillow structures.

The fine-grained massive type is aptly described by its name. It is, for the most part, a very dark, almost black, rock, with an even, fine-grained texture. Consequently it has a poor foliation and in places appears unfoliated. It commonly passes along strike into a striped hornblendic rock, where the hornblendic material is interbanded with narrow stripes of pale quartz-feldspathic material. By increase in the number of such bands, the rock takes on a markedly striped aspect, the striping being extremely delicate and persistent. The pale seams consist of bands of quartz and alkali feldspars with scattered hornblende and trails of epidote grains, the whole having a granulitic texture. Hornblendic rocks exhibiting pillow structures are commonly found within the fine-grained massive hornblendic rocks. Individual pillows are well formed though commonly elongated, so that local top-determination is possible.

These four lithological types make up a local succession at least 6,500 feet thick, and are essentially a thick monotonous series of graded subgreywacke and slate with one distinctive band of hornblendic rock.

The hornblendic rock unit is some 1,000 feet thick and occurs about 2,000 feet above the base of the exposed succession (*see* insert map on Fig. 1). These rocks are well exposed at the western end of Mesa Lake, where they form a conspicuous northerly trending ridge. Most of them are striped, the stripes varying in thickness and concentration with no apparent relation to stratigraphic level. Within the borders of the striped rocks are lenses of fine-grained, massive and pillowed hornblendic rocks. These lenses are continuous along strike for about 400 feet, range in thickness from 100 to 300 feet, and appear to be sporadically developed within the body of the striped hornblendic rocks. The lower contact of the hornblendic unit with the subgreywacke and slate is a gradational one of mechanical interfingering. Similar relations are seen at the upper contact of this hornblendic band with the overlying subgreywackes. Sections A, B, and C of Figure 1 show the hornblendic rocks wedging out to the east and west into the adjacent subgreywackes.

## Snare Group

The Snare Group comprises five rock types whose characters are described below.

*Quartz-feldspar sandstones* were mapped in the field as 'salt and pepper' sandstones because of their speckled appearance on weathered surfaces. These massive sandstones weather buff and superficially resemble the subgreywackes of the Yellowknife Group, but they are readily distinguished by their speckled appearance and their almost constant association with thin bands of calc-silicate granulites. Where found with the calc-silicate granulites these sandstones are massive with bedding obscure, although graded and current bedding are seen in places. The quartz-feldspar sandstones are also commonly associated with slaty bands. This two-fold association is common in the western half of the map-area, where thousands of feet of sediments comprise thin alternating bands, commonly only a few inches thick, of quartz-feldspar sandstone and slate.

The rocks are composed of quartz, feldspar, sericite, and chlorite, with the feldspar comprising about 30 per cent.

*Quartz sandstones* comprise a very small part of the exposed succession. They occur as thin, light coloured bands, normally 2 to 6 inches thick, intercalated with the thinly bedded quartz-feldspar sandstones and slates. These quartz sandstones are remarkably pure sediments, being composed of quartz with less than 10 per cent of chlorite and feldspar.

*Slates* within the Snare Group are similar in appearance to those in the Yellowknife Group. They are, however, even grained, commonly current bedded, and occur generally as very thin units associated with the quartz-feldspar sandstones. Each unit of slate is about 6 inches thick.

*Limestone,* found at the base of the group (Pl. IB), is composed almost entirely of coarse, even-grained crystalline calcite, is bordered with calc-silicate minerals, and weathers creamy white to buff. The base of the limestone is characterized by many thin discontinuous bands of quartz that parallel the bedding in adjacent rocks. These bands are about 2 inches thick and are regularly spaced throughout the lower 300 feet of the limestone. They are probably primary, possibly recrystallized chert bands.

*Calc-silicate granulites* occur within the Snare Group as bands and lenticles rich in calc-silicate minerals and up to 2 or 3 inches across. These small bands and lenticles show an almost constant association with the massive quartz-feldspar sandstone, and they normally appear as a finely banded, grey-green rock.

The Snare Group differs from the underlying Yellowknife Group in that graded units of subgreywacke and slate are absent and its rocks are thinly bedded. The Snare Group, with an exposed thickness of about 15,000 feet, is composed mainly of thinly bedded quartz-feldspar sandstones and slates, but includes three units of massive quartz-feldspar sandstone with calc-silicate granulites, and one unit comprising interbedded quartz-feldspar sandstone, slate, and quartz sandstone. These variations are shown as distinct units with sharp contacts on Map 1173A (*in pocket*) and also in sections C, D, and E of Figure 1, but the actual contacts between the interbedded quartz-feldspar sandstone and slate and the above variations are gradational, commonly over thicknesses up to 100 feet.

## Relation of the Snare Group to the Yellowknife Group

The Mesa Lake area straddles the northerly trending Snare–Yellowknife unconformity (Lord, 1942) in Ingray Lake map-area. Lord stated that the unconformity follows "the west side of a ridge of sheared andesitic rocks that probably belong to the Yellowknife group." It therefore lies along the upper margin of the hornblendic unit contained within the Yellowknife Group. On examination, this contact was found to be partly obscured by later shearing related to the deformation of the Snare Group. At points where shearing has not affected the relations between the hornblendic rocks and the overlying subgreywacke and slate, the contact is gradational with no visible evidence of overlap or erosion. The hornblendic rocks were interpreted by Lord (1942, p. 20) as being the oldest member of the Yellowknife Group; they, in fact, appear to be underlain by a considerable thickness of subgreywacke and slate.

Outside of Mesa Lake map-area, the 'unconformity' is invariably a gradational contact (Ross and McGlynn, 1958). Conglomerate was found at the localities cited by Lord (1942, pp. 20-22), but the rounded boulders comprising these conglomerates are scattered above and below the line of the supposed unconformity, with no sign of erosion. These boulders were probably deposited at the same time as the subgreywacke that forms the matrix of the conglomerates, rounding of the boulders having taken place under conditions different from those then existent at their present site. This antipathetic association of coarse rounded granitic boulders with greywackes has been described by Tercier (1947), Miglorini (1949; 1950), and notably by Keunen and Miglorini (1950), who have, so far, advanced the most satisfactory explanation for their origin, such that the presence of these rounded boulders is no indication of erosion or of a time break, but rather of conditions of sedimentation.

Within Mesa Lake map-area, evidence of unconformable relations between the Yellowknife and Snare Groups is lacking, although south of the area, near the north end of Basler Lake, such relations are unmistakably clear. There, the base of the Snare Group is marked by a conspicuous limestone that lies unconformably upon greywackes and slates of the Yellowknife Group. Further, the Snare Group rocks at this locality are only slightly deformed. As this unconformable contact is traced northwards, the rocks of the Snare Group become more intensely deformed and the unconformable relations between the two groups become less apparent, whence, within the Mesa Lake area evidence of an unconformity separating Snare and Yellowknife rocks is totally lacking.

Separation of the two groups is based largely upon field evidence outside of the Mesa Lake area.

# STRUCTURAL GEOLOGY

## Introduction

Outcrop mapping on the scale of 2 inches to 1 mile has enabled the author to record and analyze a large amount of structural data (the orientation of bedding planes, axial planes of minor folds, linear structures, and minor fold axes). The traces of the major fold axes on the ground surface, as shown on Figure 2 (*in pocket*), have been obtained by using the ever-present sedimentary structures and by joining the fold hinges, the latter having been recognized by change in strike and dip of the bedding planes.

For the purpose of structural analysis, the map-area has been subdivided into 17 areas, each covering from 3 to 10 square miles, the size depending upon the complexity of the local structure. Within each of these subareas some 200 to 300 measurements of orientation of bedding planes were noted and the poles to these measurements were plotted and contoured on a stereographic net (lower hemisphere projection, Fig. 3, *in pocket*). The orientation of linear structures was plotted on the same diagrams, but left uncontoured. Poles to the measurements of the axial-plane cleavage and axial planes of minor folds have been plotted on Figure 4 (*in pocket*). With the data plotted in this manner it can be seen that the major and minor structures are consistent. The poles to the bedding planes all lie on a great circle whose pole coincides with the plots of the relevant linear structures. Thus, locally the folds can be classed as cylindrical, and by study of the change in orientation of the fold axes from subarea to subarea the geometry of the major structure, as a whole, may be more clearly understood.

### Fold Sets

Three distinct sets of folds and associated minor structures were found in the map-area. The first occurs in the northeastern part, around Arrow Lake, where folds with northerly trending axial-plane traces can be recognized. The style of these folds is characteristic, as they consist of anticlines and synclines whose limbs are steep, dipping to the east at about 65 to 75 degrees. The folds plunge to the south at fairly shallow angles. A well-developed axial-plane cleavage, which dips to the east at about 80 degrees, parallels the axial-plane traces of these major folds.

From Arrow Lake southwards into the area around Dune Lake, the northerly trending folds have been bent around an axis that plunges steeply to the southeast. This distortion marks a second set of folds whose axial traces trend in a northeasterly direction, and whose direction and amount of plunge are variable. These



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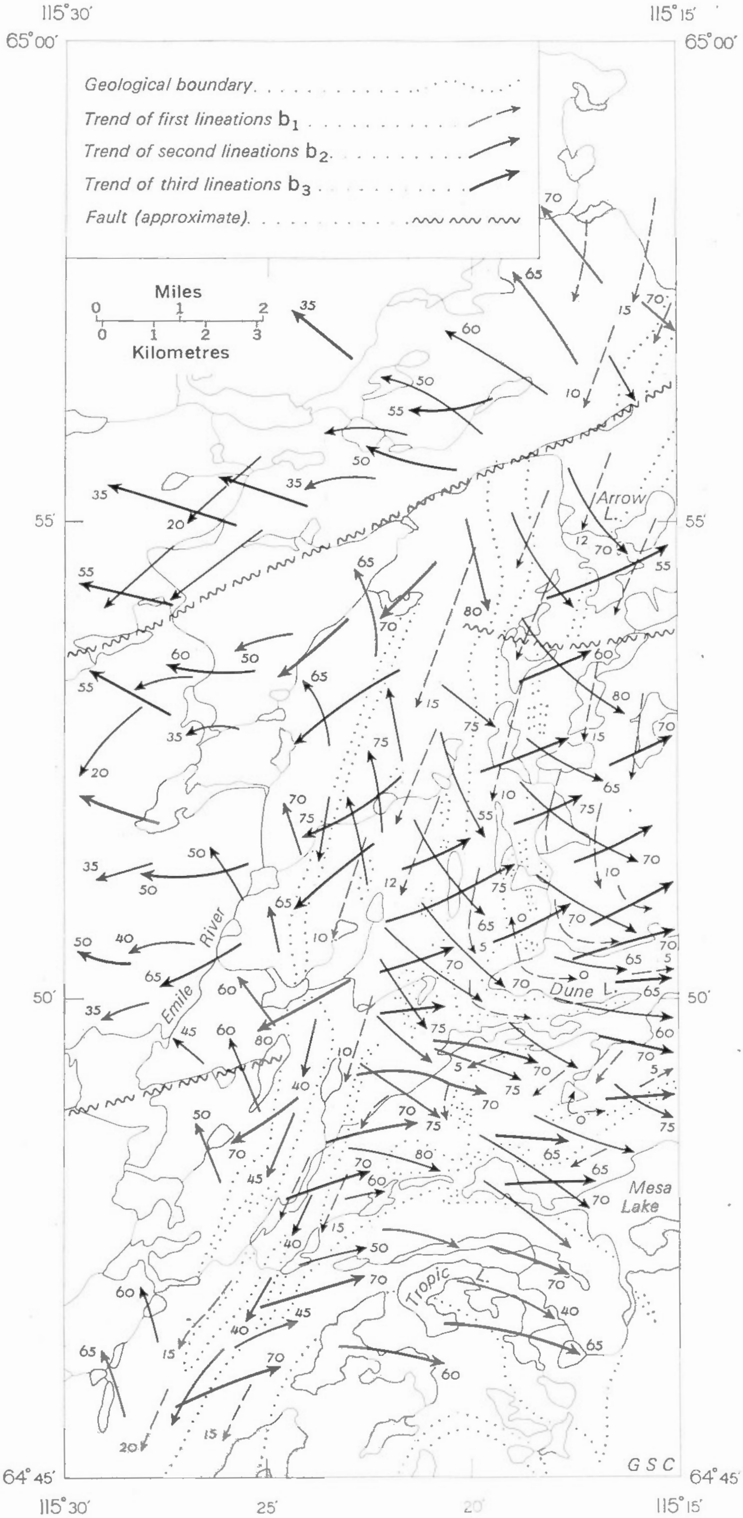



**FIGURE 5. Trends of lineations.**

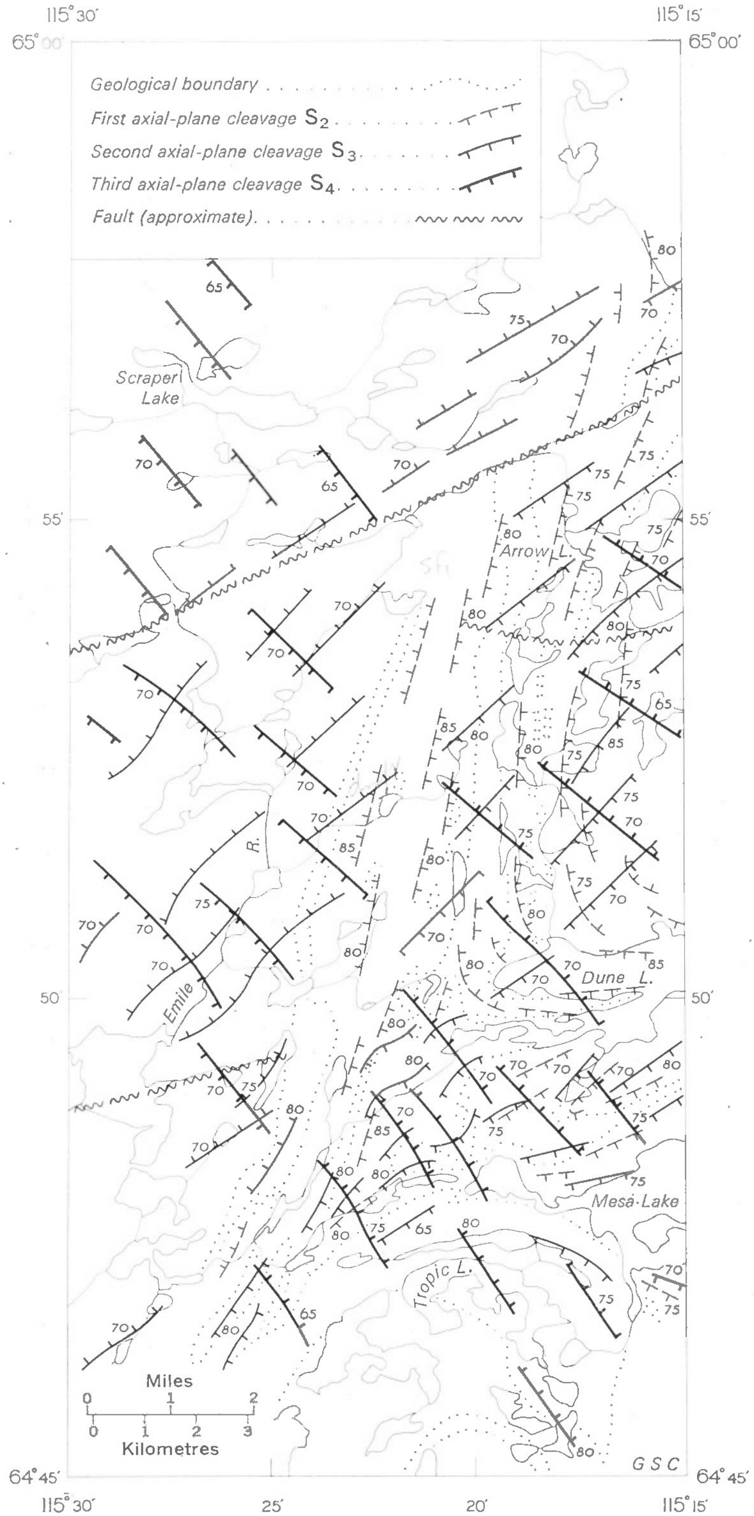



**FIGURE 6. Trends of axial-plane cleavages.**

second folds are superimposed upon the northerly trending first folds. Slide planes along boundaries between competent and incompetent beds and along the unconformity between the Yellowknife and Snare Groups were developed during the second-fold movements, and at the same time the first folds underwent further closure owing to the superposition of the second folds.

A third set of folds, whose axial planes have a constant northwesterly trend, was superimposed upon the first and second sets. Folds of this third set are well developed on the eastern flank of the major (northerly trending) first fold northwest of Mesa Lake. As these third folds are superimposed upon first folds that had already been distorted by the second-fold movements, the result is a complex easterly plunging structure. Folds developed during this third phase of folding also occur on the western and northwestern flanks of the major first fold, but there they are gentle warpings of the first-fold structure, and do not show evidence of the intense deformation that characterizes the rocks near Mesa Lake.

Each of the three periods of folding was characterized by the development of a set of minor structures—lineations, axial planes of minor folds, minor folds, and axial-plane cleavage. The trends of the linear structures and axial-plane cleavage related to the different phases of fold movements are shown in Figures 5 and 6, and indicate a history similar to that suggested by the major structures.

The final phase of the formation of the structure in Mesa Lake map-area (probably some considerable time after the termination of folding) was the development of two northeasterly trending tear faults, each having a right-handed sense of displacement.

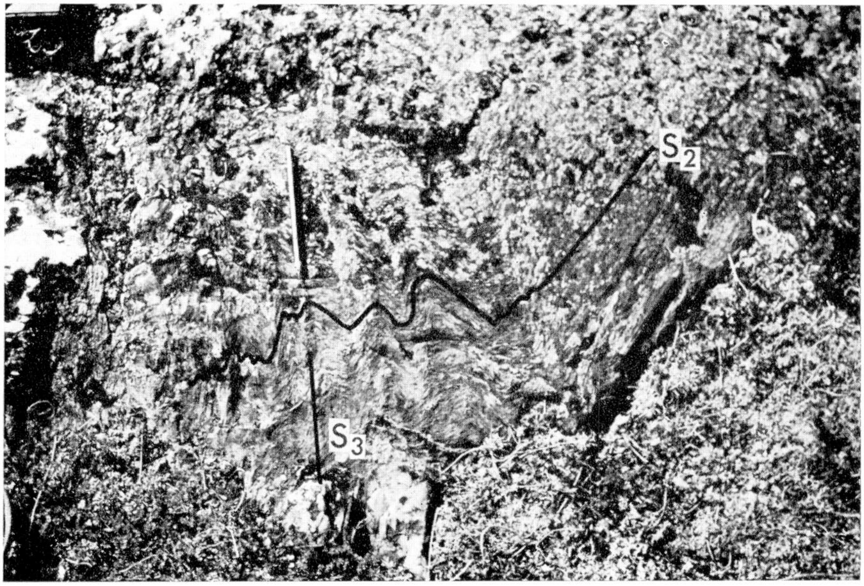
## Planar Structures

### *Foliation Planes ($S_1$)*

Several megascopic foliation planes were observed in the rocks of Mesa Lake map-area, the most prominent of which is defined by alternating layers of differing mineralogical composition and represents original sedimentary variation. This foliation, designated $S_1$, is parallel to the boundaries of rocks of differing composition and is therefore interpreted as bedding. Commonly this bedding is outlined by the basal plates of micaceous minerals and prismatic minerals, the long direction of the latter always being contained within the plane of the bedding.

### *Foliation Planes ($S_2$, $S_3$, and $S_4$)*

Small folds related to the first-fold structures exhibit a cleavage that is parallel to their axial planes. This is designated $S_2$, the first axial-plane cleavage, and is commonly defined by the orientation of basal planes of micas parallel to the axial planes of these small folds. This cleavage is well developed and is consistent in direction of strike and dip only in areas where the first-fold structures are unaffected by later folding. Around the western end of Mesa Lake and the northern

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A. Phyllitic rock at western end of Mesa Lake. Axial-plane foliation $S_2$, progressively crinkled about foliation $S_3$.

## PLATE II

B. Phyllitic rock, southwest of western end of Mesa Lake. Two well-developed linear structures are shown with $b_1$ disjointed by the superposition of $b_2$.


112720-D

reaches of Emile River this foliation, $S_2$, is folded and partly destroyed by later fold movements (Pl. IIA). These later fold movements comprise two directions of folding, both having similar style but differing in direction and time. Each of these later fold directions commonly shows a well-developed axial-plane cleavage, denoted $S_3$ and $S_4$, the second and third axial-plane cleavages, respectively.

## Axial Structures

### *Major Fold Axes ($B_1$, $B_2$, and $B_3$)*

The ground traces of the major fold axes are shown on Figure 2. Three sets of fold axes have been recognized from the stereographic-net plots of the poles of foliation $S_1$ for each of the 17 subareas within the map-area (Fig. 3). The points representing these poles, when contoured, always lie on a great circle, the pole of which corresponds to the direction and amount of plunge of that fold axis within the subarea concerned. As stated previously, the limbs of the first major folds, $B_1$, have been folded about new axis, $B_2$, and both axes were in turn folded about a further axis, $B_3$.

### *Lineations ($b_1$, $b_2$ and $b_3$)*

Well-developed linear structures are prominent (Pl. IIB). They are found in all rock types and appear to be best developed in the crests and troughs of folds. All are parallel to the fold axes of one or another of the three major directions of folding. Five types of lineations were recognized and mapped.

*Cleavage-bedding intersection*–small folds commonly show a well-developed axial-plane cleavage that is defined by a planar orientation of micaceous minerals. The intersection of this cleavage and bedding, $S_1$, has produced fine lines on the bedding planes.

*Minute corrugations of the foliation planes* have given rise to a linear structure, which is as common as the type described above.

*Quartzo-feldspathic rods* occur within the rocks showing a high degree of metamorphism and migmatization, their direction of elongation lying in the axial planes of small folds and parallel to their axes. Small augen of quartz and feldspar are also found in these rocks, and these too are elongated parallel to the local axis of folding.

*Mineral orientation*–a common lineation, is produced by the orientation of the long axes of prismatic minerals, especially hornblende. Cordierite and sillimanite, which developed during metamorphism, are also elongated, and their direction of elongation is always parallel to the axes of nearby folds. The parallelism of quartz and quartzo-feldspathic rods and the direction of elongation of metamorphic minerals to the local fold axes lead to the suggestion that metamorphism and migmatization accompanied each of the three periods of folding.

*Minor folds* are common and the orientation of their axes is consistent over small areas and is always parallel to other nearby linear structures.

Linear structures are associated with each of the three directions of folding. Throughout the map-area the oldest linear structures are parallel to the first fold axes, and are designated the first linear structures, $b_1$. Two later linear structures, which are related to northeast-southwest and northwest-southeast systems of folding, are referred to as the second linear structures, $b_2$ and the third linear structures, $b_3$.

## Structural Events

### First-Fold Movements

The earliest recognizable tectonic event within the map-area appears to have been the development, within the Yellowknife Group, of a series of northerly trending fold structures, $B_1$, having a shallow plunge to the south. Associated with the development of these folds were widespread linear structures, $b_1$, that have a plunge parallel in direction and equal in amount to the major fold axes. The trends of lineations $b_1$ are shown on Figures 3 (Nos. 5, 6, 9, 10, and 15) and 5.

Evidence of first folding along this northerly trend is apparent in nearly all outcrops of the Yellowknife Group. In the regions about the west end of both Mesa Lake and Dune Lake, however, original structures related to the first-fold movements have been almost obliterated by the succeeding second- and third-fold movements. Where the effects of this first northerly trend are still apparent, the form of the folds is a series of anticlines and synclines, whose limbs are nearly parallel and dip steeply, at about 75 degrees, to either the east or the west. The axial traces of these folds trend approximately N15°E and the lineations, $b_1$, plunge southerly at angles of 10 to 15 degrees. The axial planes and axial-plane cleavage, $S_2$, dip steeply to the east or to the west at about 75 degrees (Fig. 4, Nos. 5, 6, 9, 10, and 15). The stereograms of the structural data from subareas 5 and 10 on Figure 3 show this northerly trend, with a shallow plunge of the $b_1$ structures to the south. This direction of plunge varies regularly in an anti-clockwise direction through some 20 degrees, where the direction of $b_1$ structures in subarea No. 3 (Fig. 3) is 203 degrees, while in subarea No. 10 the direction of plunge of the $b_1$ structures is 182 degrees. This variation in the direction of plunge, from north to south, while the amount of plunge is practically unchanged, can be shown to be the result of later movement about a $B_3$ axis.

To the west of the hornblendic unit, these easterly dipping first structures steepen, and there is a northerly trending zone of vertical beds about 100 yards wide. West of this vertical zone, the limbs of the first-fold structures all dip west and each fold has one steep and one shallow limb. The axial planes and axial-plane cleavages from these western first-fold structures also dip steeply to the west (Fig. 4, Nos. 6, 9, and 15). Although there is a change of symmetry of the first-fold structures from east to west, through a narrow vertical zone, their direction and amount of plunge are practically constant. This vertical zone corresponds to the position of fold trace No. 4 on Figure 2 and is anticlinal in nature, with a complementary synclinal fold immediately to the east (fold trace No. 3 on Fig. 2). The form of these folds has been established by the use of minor folds and graded bedding observed within the associated subgreywackes (Fig 8). The stereograms of foliation planes from the subareas 9 and 15 on Figure 3 show incomplete girdles with two well-developed maxima. Lineations within these subareas fall into three marked groups, the $b_1$ lineations occupying areas that correspond to the poles of the incomplete girdles. The poles of the great circles through the incomplete girdles of stereograms Nos. 9 and 15 on Figure 3 are 196°/20° and 190°/40°, respectively, which are the local plunges of the first fold structures. Thus, since $b_1$ lineations occupy the positions that correspond to the poles of the great circles through the foliation plane maxima, these first structures have undergone little or no rotation about the later fold axes $B_2$ and $B_3$.

Small minor folds developed on the limbs of the major structures have a geometric form similar to that of the major folds. They have steep and gentle limbs and axial planes parallel to those of the major structures, and exhibit a sense of movement that is consistent with the uppermost beds having moved away from a synclinal core to anticlinal crests (Fig. 7). This sense of movement, indicated by the small folds, was noted throughout the area, and serves as an extra aid in understanding the geometry of the entire structure.

## Second-Fold Movements

The second tectonic event in the map-area was the deformation of the Snare Group, together with the modification of the already deformed Yellowknife Group. The folds, $B_2$, produced at this time are characterized by northeast axial traces, and achieved their most interesting development where superimposed upon the already deformed Yellowknife rocks.

The second, $B_2$, folds are well developed at the western end of Mesa Lake and in the area west and southwest of Scraper Lake, and decrease in intensity westwards and southwards. Where undeformed by the third-fold movements, they are fairly open structures with steep plunges, and their geometry is dependent upon the attitude of the limb or limbs of the first folds upon which they have been superimposed. Near Mesa Lake where the limbs of the first-fold structures dip steeply to the east, the second folds plunge steeply to the southeast.

### *New Structures*

*The Major Second Folds ($B_2$)*

The positions of the major second folds are shown on Figure 2 (fold trace Nos. 5, 6, 7, 8, 9, 10, 14, and 15).

The most interesting second-fold structures occur near the western end of Mesa Lake where a series of second folds, whose axial traces trend NE-SW, have been superimposed upon the older northerly trending structures. Fold trace No.

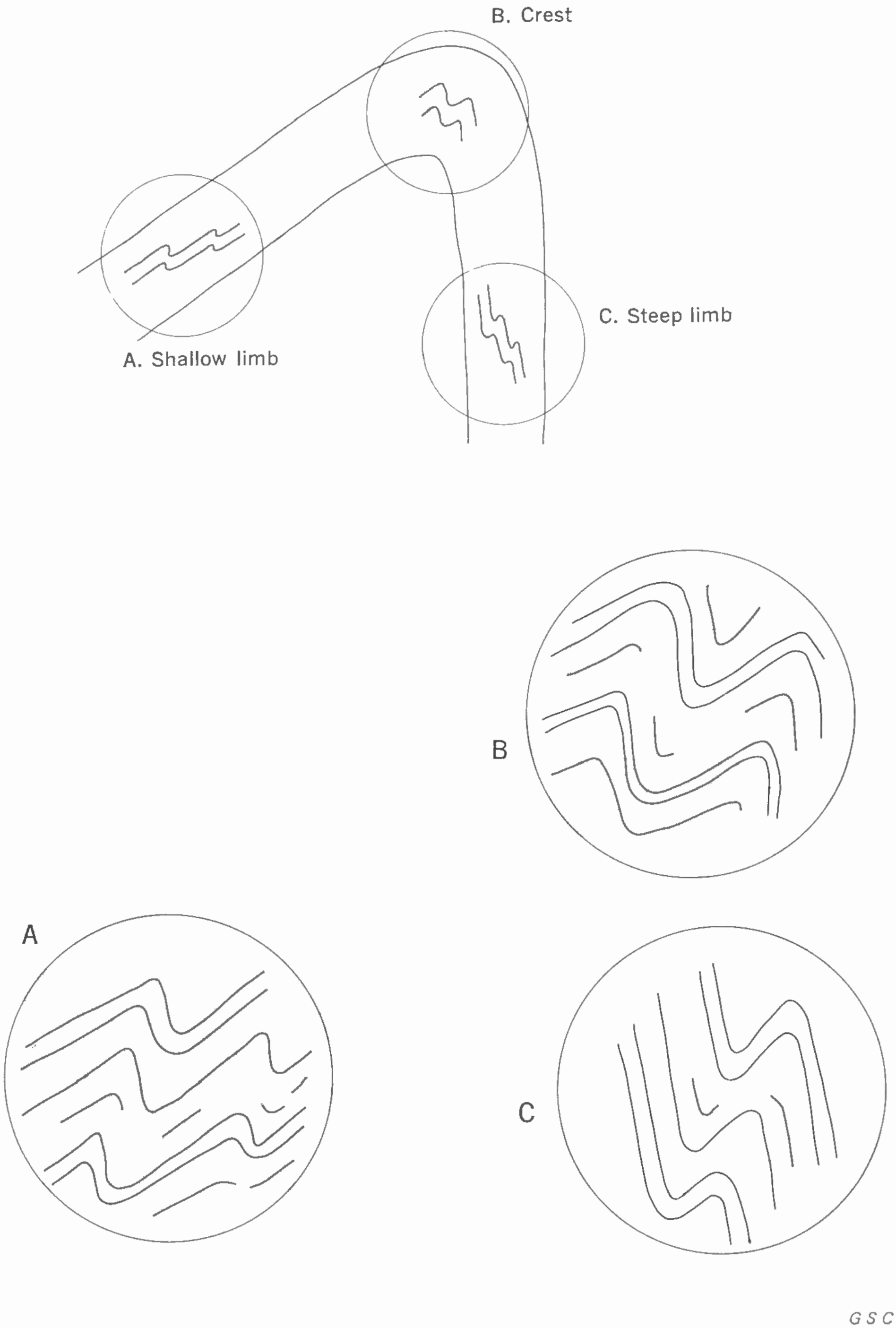



**FIGURE 7. Sketch showing minor folds situated on the limbs and crests of the first folds.**

7 (Fig. 2) is related to a steeply plunging fold, whose geometry is characteristic of these second folds. The axial plane of this fold trends N46°E and dips 75°SE. This second structure (fold No. 7, Fig. 2) has refolded the limbs and axial planes of two first folds (Nos. 1 and 2, Fig. 2), the hinge of this new structure being at the extreme western end of Dune Lake. The stereogram of foliation-plane poles from this area (Fig. 3, No. 11) shows two well-developed maxima, which correspond to the two limbs of the second fold. Great circles, which have these two maxima as their poles, intersect at a point that corresponds to the fold axis $B_2$, about which the northerly trending first folds have been rotated. This $B_2$ axis plunges 74° in the direction S46°E (134°/76°) and coincides with the concentration of $b_2$ lineations plotted in No. 11 of Figure 3. This is the characteristic geometry of the second folds. It is impossible to classify these folds as anticlines or synclines, because the plunge of the strucure is everywhere to the southeast down the dip of its axial plane. They are sideways closing folds, and could be called inclined folds.

Other folds, developed during the second period of folding parallel to fold trace No. 7 (Fig. 2), are present between Dune Lake and the western end of Mesa Lake. These are all inclined folds that plunge steeply down their axial planes to the southeast, and appear to be smaller folds on the northern limb of a much larger similar structure, whose axial trace trends in a southwesterly direction through Mesa Lake. This larger structure has a southern limb that was a mirror image of the northern limb with its inclined folds, but which underwent intense deformation during a third period of folding and consequently now presents an aspect completely different from that seen on the northern limb. Evidence for the deformation of the southern limb during a third period of folding, and its appearance prior to this folding, is presented later.

During the development of these second-fold structures, sliding took place along the unconformity between the rocks of the Snare and Yellowknife Groups. The disposition of these slides or fold-faults is shown on Figure 8. The main effect of sliding was to thicken and thin basal limestone along the strike. Movement along this unconformity probably brought about the development of the second folds on the limbs of the first-fold structures.

The limestone is strongly attenuated in a northerly direction about the No. 3 synclinal fold shown on Figure 2 (*see also* insert map on Figure 1). At the northern end of the limestone closure, the northerly continuation of this synclinal fold axis is marked by a narrow (about 20 feet wide) continuous zone of disturbed ground. The subgreywackes within this zone are characterized by extreme crinkling of their bedding surfaces, $S_1$, the plunge and axial planes of these crinkles being parallel to $b_2$ and $S_3$, respectively. The subgreywackes on either side of the crinkled zone, however, exhibit graded bedding, which yielded top determinations that suggest a synclinal axis lying within the crinkled zone.

This zone has been traced northwards for several miles within the subgreywackes. About 3 miles north of the limestone closure, it approaches the boundary

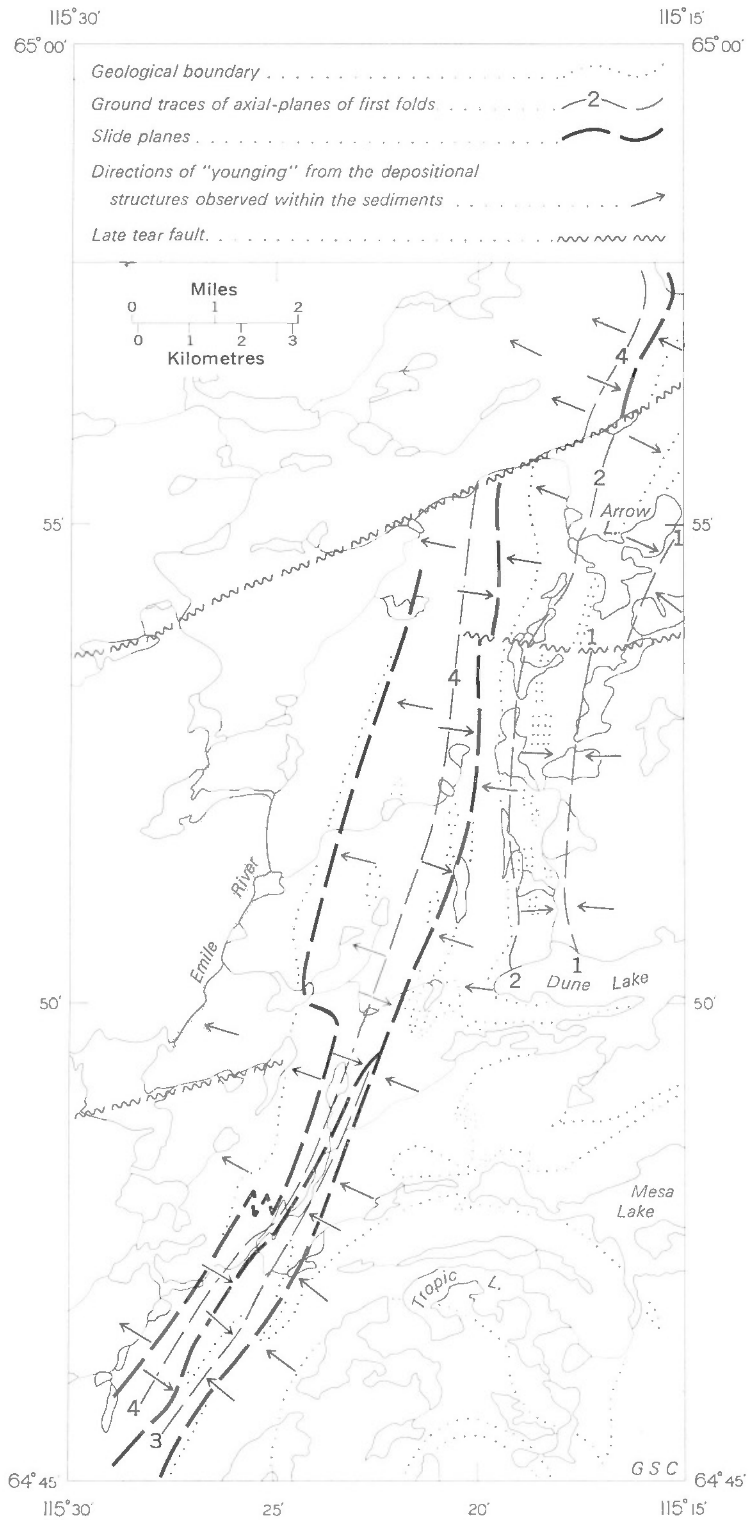



**FIGURE 8.** Form of first folds and locations of slide planes developed during the second- and third-fold movements.

between the subgreywacke and the hornblendic unit. From there to the northern margin of the map-area, the zone of disturbance lies along the contact between these two rock units. It is probable that sliding was not confined to a single set of planes, but rather has been distributed over a host of close-set parallel planes. In this way thinning of groups of rocks, mainly subgreywacke, and the disappearance in a northerly direction of fold trace No. 3, may be accounted for.

Folds related to the second period of folding are well developed in the Snare Group west and south-southwest of Scraper Lake, in the northwestern part of the map-area. The axial traces of these second folds trend N36°E, dip steeply (about 75 degrees) to the northwest, and have a variable plunge to the southwest.

*Second Axial-plane Cleavage ($S_3$)*

A cleavage parallel to the axial planes of the major second folds, $B_2$, is fairly well developed over most of the area mapped. It has a reasonably constant northeasterly strike, except where it was involved in the third-fold movements; it dips to the northwest in the west and northwestern parts of the map-area and to the southeast in the eastern part. This change of dip direction of the second axial-plane cleavage, $S_3$, is along a north-south line that corresponds to the No. 4 fold trace on Figure 2, which is related to an anticline developed during the first-fold movements. The two succeeding fold movements probably caused further closure about this major first-fold anticlinal axis such that fold traces Nos. 1, 2, and 3, which are all related to the first-fold movements, can be considered as minor folds on the east and west limbs of this major anticlinal structure. All later structures are essentially developed on the limbs of this steeply dipping first structure, some of the movement being taken up along the slide planes shown on Figure 8. Thus, the attitudes of the succeeding structures are controlled by the attitudes of the limbs of this major anticlinal first structure. Trends of the axial-plane cleavages are shown on Figure 6; these cleavages are confined to the limbs of this major anticlinal first fold, and are related to distortions superimposed upon its limbs.

*Second Linear Structures ($b_2$)*

The trends of the second lineations, $b_2$, are shown on Figure 5; these lineations exhibit wide variations in direction and amount of plunge, which result from the varying inclination of the intersections of the limbs of the first-fold structures with the fairly constant axial planes of the second folds. In the eastern part of the map-area, north of Dune Lake, tracing of the major and minor second folds southwestwards across the first folds reveals that the steeply northeasterly plunging second lineations change their orientation and plunge steeply to the south or southeast.

The area in which the first folds appear to be practically undeformed by the second folds coincides with subareas 5 and 10 on Figure 3. Figure 9 shows the investigation of a strip of country within subarea 5. Poles to the foliation planes, $S_1$, on either side of axial trace No. 2 have been plotted, and from these the east and west limbs of the fold No. 2 have been constructed. The average axial plane of the second folds, as found from data plotted on Figure 4, No. 5, intersects the east and west limbs of the folds at points that correspond to the plunges of the second linear structures. On the east limb of the first structure the superimposed second lineations plunge to the southeast at 70 to 80 degrees, whereas on the west limb they plunge to the south at 60 to 65 degrees. Figure 10A is a composite diagram of the second lineation plots from subareas east of fold trace No. 4. These lineations obviously fall into two groups, which correspond to the calculated values of the second linear structures shown on Figure 9.

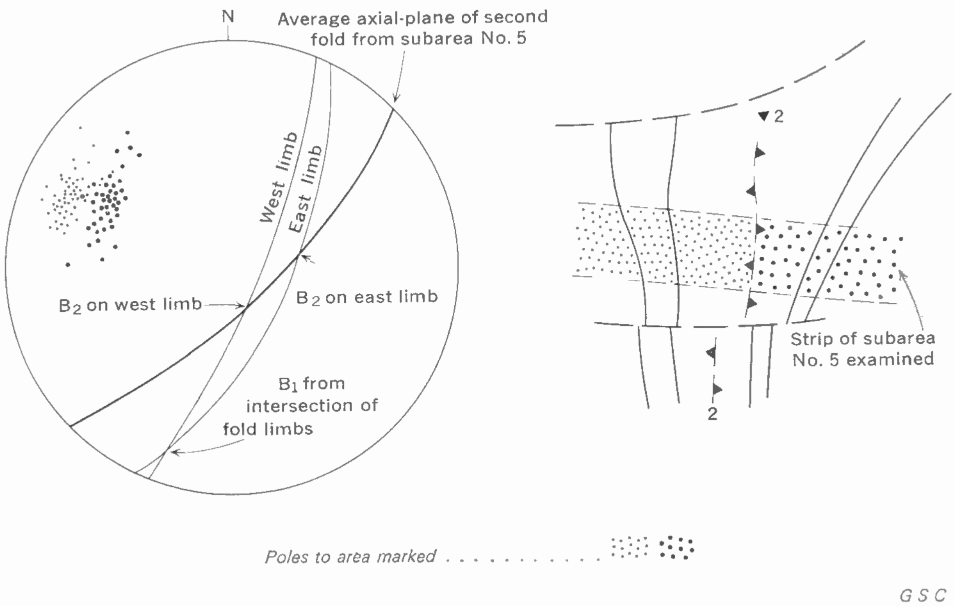



FIGURE 9. Diagrams showing structural analysis of a strip of ground across fold-trace No. 2 in subarea 5.

Within the Snare Group and west of the first fold axial trace No. 4 (Fig. 2), the axial planes of the second folds strike in approximately the same direction as they do to the east of this first fold axis No. 4, but they dip steeply to the northwest. Composite diagram Figure 10B shows that the second-lineation plots from west of first fold trace No. 4 also fall into two well-marked groups that plunge westerly and northeasterly at about 70 and 45 degrees, respectively. Calculated values for the second linear structures west of first fold axis No. 4, constructed in a manner similar to that used for the preparation of Figure 9, appear as two points, which coincide with the two marked groups of the second lineation fields in composite diagram Figure 10B.

Thus, these second lineations, $b_2$, plunge at various angles down the dip of the almost constant second axial planes, $S_3$, and are all contained within this axial plane; the variation in direction and amount of plunge depends upon the attitude of the first-fold structures upon which the second structures have been superimposed.

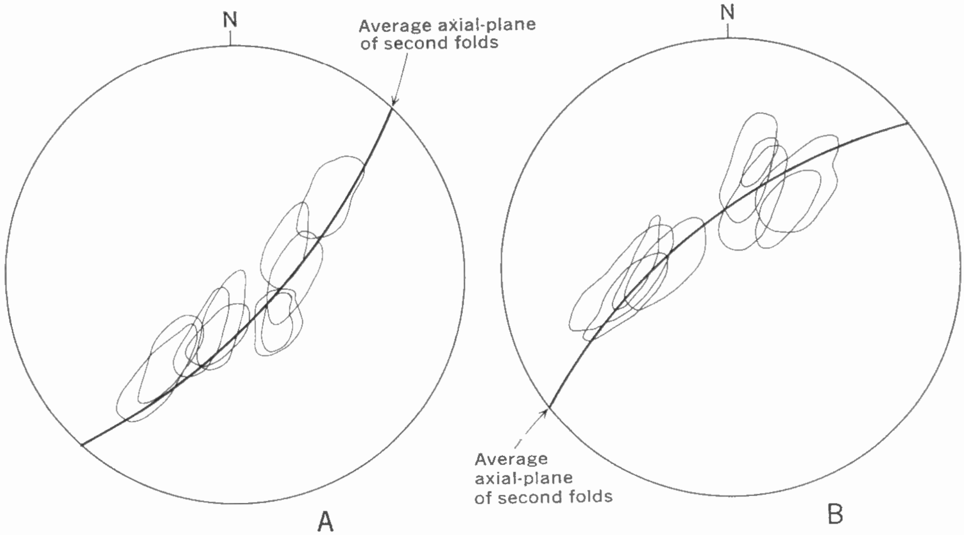



FIGURE 10. Composite diagrams of second lineation ($b_2$) fields from subareas east (A) and west (B) of first fold-trace No. 4.

### *Deformation of First Folds and Their Associated Minor Structures*

The superposition of the second folds upon the northerly trending first folds resulted in the refolding about new axes of the limbs, axial planes, and linear structures of these first folds.

*Distortion of the Major Folds ($B_1$) by the Second Major Folds ($B_2$)*

In the northeastern and southwestern parts of the map-area, the first fold axes, $B_1$, were relatively undisturbed by the second-fold movements. Evidence of their deformation by the second folds is a slight warping of the foliation planes about new axes. These new axes have variable amounts of directions of plunge, which were controlled by the attitude of the limbs when they were refolded. The new fold axes are shown as plots of second lineations, $b_2$, in Figure 3 (Nos. 5, 6, 8, 9, 10, 14, and 15), and in these seven subareas, where the effect of the second folding is slight, these fold axes are obviously unrelated to the E-W girdle of foliation-plane poles, which was produced during the development of the first folds.

Near Dune Lake, the first folds are strongly deformed about the second fold axes, $B_2$. Poles to foliation planes, $S_1$, from this region are shown in Figure 3, No. 11, which displays a girdle with two well-defined maxima. Great circles, whose poles correspond to these maxima, intersect at a point occupied by the position of the second lineations, $b_2$. In the same diagram, plots of the first lineations, $b_1$, exhibit a marked scatter, and are obviously not related to the girdle of foliation plane poles, $S_1$, which was formed during the development of the second folds. Thus, the new structure is a steeply plunging cylindrical fold whose limbs are represented by the two maxima within the girdle of diagram No. 11 on Figure 3.

*Distortion of Axial-plane Cleavage ($S_2$) and Minor First Folds by the Second-Fold Movements*

The first axial-plane cleavage, $S_2$, like the first fold axis, $B_1$, was relatively undisturbed within the northeastern and southwestern parts of the map-area.

Near Dune Lake, however, where the second-fold movements were intense, the axial-plane cleavages, $S_2$, are bent from a northerly direction to an easterly direction as they pass into the southern limb of fold No. 7, shown on Figure 2. To the south of this No. 7 fold, and towards Mesa Lake, evidence of similar deformation of the first axial-plane cleavage, $S_2$, by the second-fold movements is seen. This change in orientation of the first axial planes is shown on Figure 6 and also in the stereographic projections Nos. 11 and 12 on Figure 4.

Two separate diagrams have been constructed (Figs. 11A and B) showing the plots of the first axial-plane cleavage, $S_2$, on the west and south limbs of the second fold No. 7, shown on Figure 2. Within each diagram the poles of the axial planes, $S_2$, scatter along a great circle whose pole is the axis of folding of these axial planes.

In the same diagrams the axes of folding of the foliation planes, $S_1$, from each of the two limbs (from No. 11 of Fig. 3) have been superimposed. It is readily seen that the axis of folding of the axial planes, $S_2$, from each of the limbs

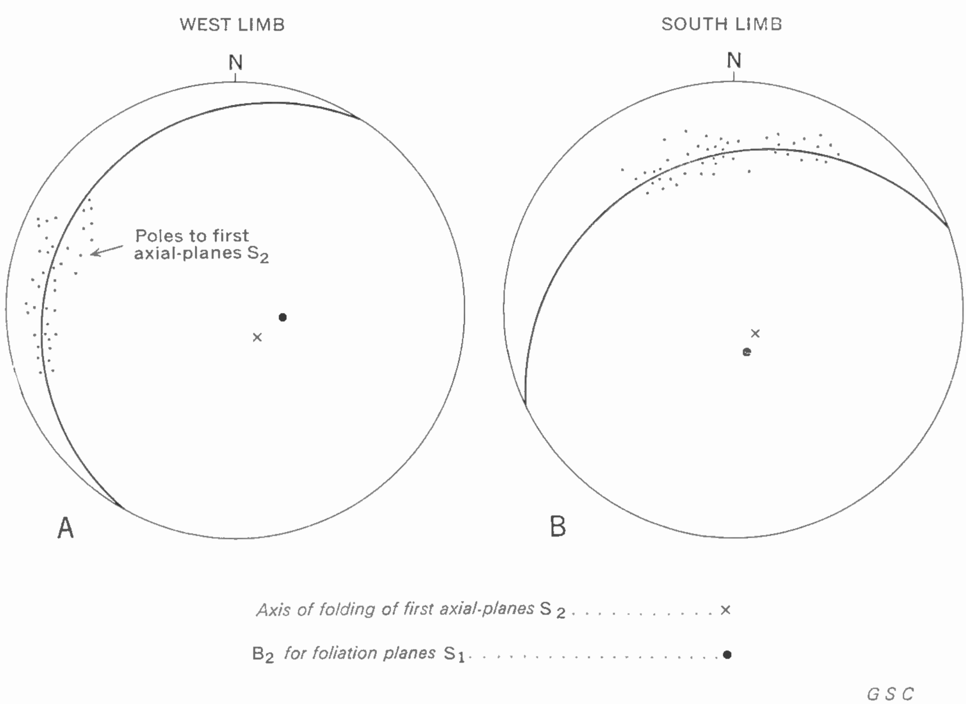



**FIGURE 11. Diagrams showing the distortion of axial-plane cleavages ($S_2$) about the second-fold axis ($B_2$) in subareas 10 and 11.**

of this second fold does not coincide with the axis of folding of the foliation planes, $S_1$, but lies between the two. This difference in axis of folding on the two limbs is probably the result of plastic deformation during the second period of folding.

Minor folds related to the first-fold movements, whose axial-plane deformation has been described above, show marked geometric differences when involved in the second-fold movements. These differences vary with the intensity of the second deformation.

The minor first folds (Fig. 7) commonly have long limbs and small wave lengths, whereas the second minor folds are commonly angular wrinkles with small amplitude. Where the first minor folds have been involved in the second-fold movements they have been refolded about new axes, and the resulting geometric form is dependent upon the angular relation between the first-fold limbs and the second axial planes. Examples of this relation can be seen in outcrops in subarea No. 11 (the location of which is shown on the inset map on Figure 3), and Figures 12A and B show the orientations of the two sets of minor folds.

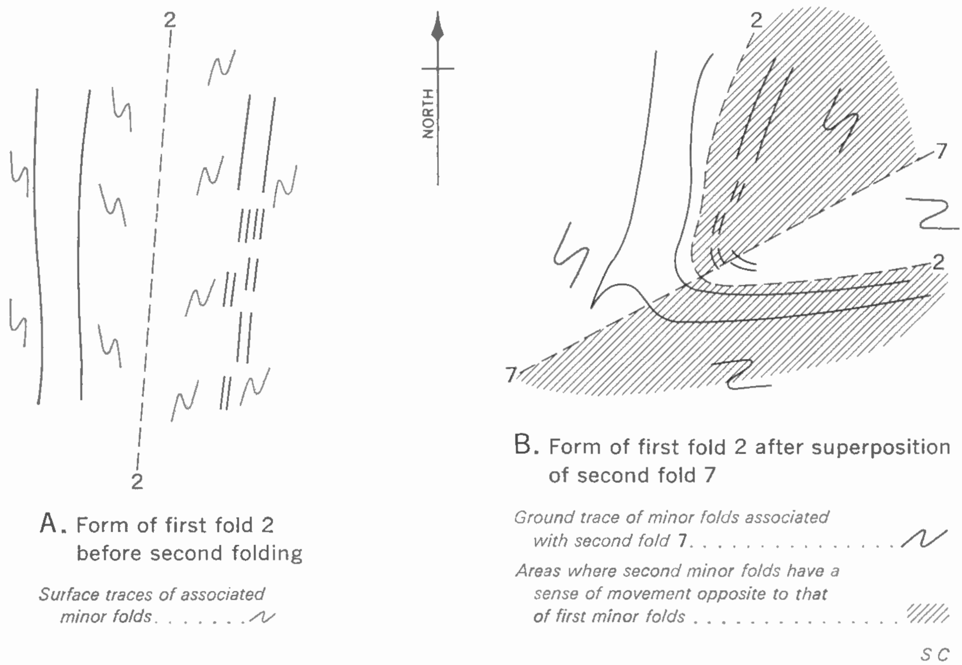



FIGURE 12. Diagrams showing the relation between the first and second minor folds within subarea 11.

Where the sense of movement of the two sets of minor folds is the same, the first minor folds merely show extension and thinning of their limbs (Fig. 13A), but where the sense of movement of the two sets of minor folds is opposed, the first minor folds are refolded in various degrees according to the intensity of the second-fold movements (Fig. 13B).

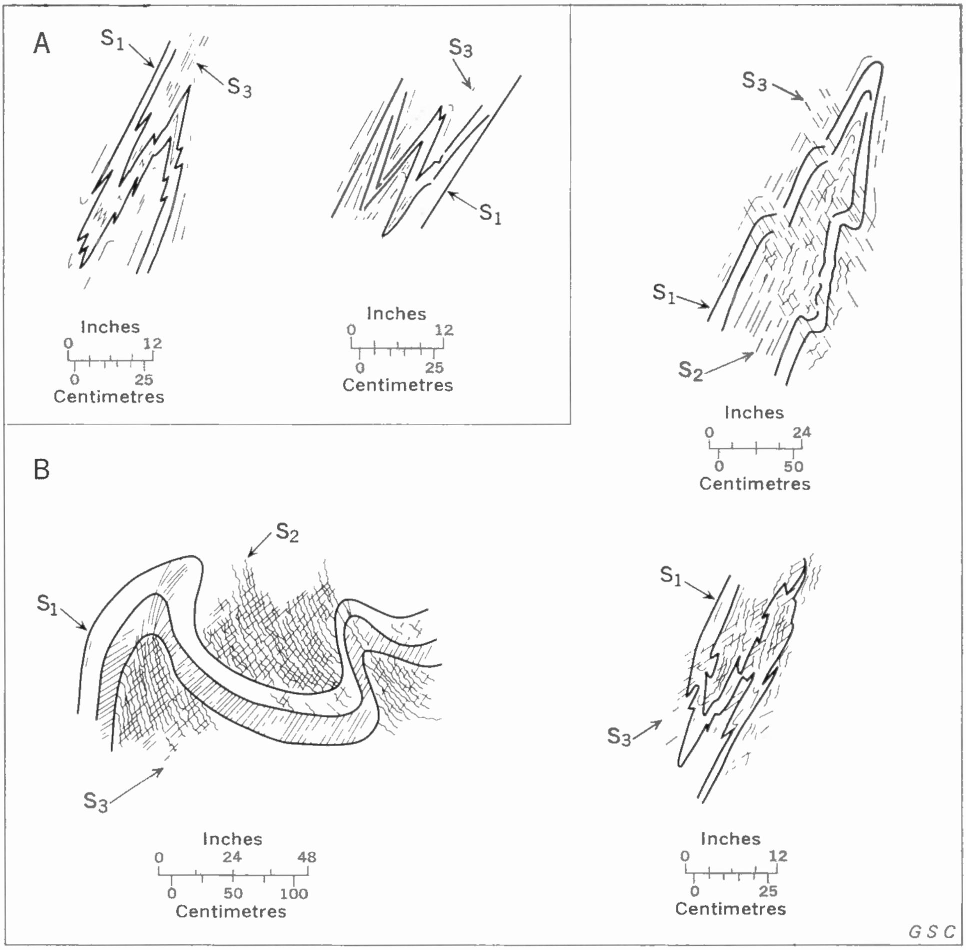



FIGURE 13. Field sketches of minor folds deformed by the second-fold movements.

*The First Lineations ($b_1$) Deformed by the Second-Fold Movements*

At the same time as the first axial planes were deformed by the second-fold movements, the lineations contained within the first axial planes were also refolded. The trends of these first linear structures are shown on Figure 5. These first linear structures are fairly well preserved throughout the area mapped, except near Mesa Lake where the second- and third-fold movements were intense and most of the first minor structures have been obliterated. This preservation of first minor structures is especially marked in the cores of first folds, since refolding of the first folds commonly causes further closure about their original axes and results in the local generation of further structures parallel to those axes. However, most outcrops show relics of the first linear structures, which can be traced around the hinges of the minor second folds (Fig. 14). The angle between the first and second lineations is variable and systematic, for the orientation of the second lineations is a function of the steepness of the limbs that were refolded.

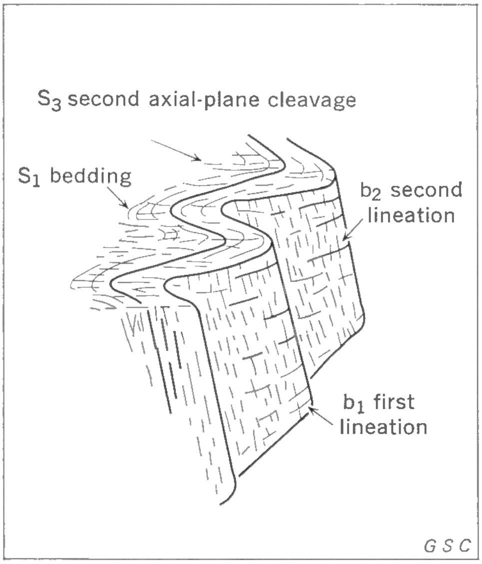



FIGURE 14. The relation between the second lineations ($b_2$) and the first lineations ($b_1$)—crinkling of the first by the second.

## Third-Fold Movements

Most of the third-fold movements are confined to the northwestern and southeastern parts of the map-area, and have resulted in the formation of a third set of folds, $B_3$, whose axial traces trend in a northwest-southeast direction. This third set is developed upon the east and west limbs of the first major anticlinal fold, whose closure had already been accentuated by the previous superposition of the second folds. The geometric form of the third folds is similar to those developed during the second-fold movements. They are normally open structures with steep plunges and are especially well developed near the western end of Mesa Lake, where they are superimposed upon both first- and second-fold structures.

### *New Structures*

*Major Third Folds ($B_3$)*

The axial traces of the third major folds are shown on Figure 2 (Nos. 11, 12, 13, 17, 18, and 19). The most intense third-fold movements occurred at the western end of Mesa Lake, whereas the third folds developed in the northwestern part of the map-area, near Scraper Lake, are only gentle warps superimposed upon the pre-existing first folds.

At the western end of Mesa Lake the structure is complex, as both second and third folds have been superimposed upon the northerly trending first folds, and in this locality much of the evidence of folding along northerly trending axes has been destroyed. Further movement along slide-planes that were initiated during the development of the second folds accompanied the third period of folding in the eastern part of the map-area; the slide-planes themselves were slightly warped during these third-fold movements.

Fold traces Nos. 11, 12, 13, in Figure 2 mark the positions of steeply plunging folds, whose axial planes trend N40°W and dip 70°NE. These are third folds that have refolded the axial planes and limbs of second folds Nos. 7, 8, 9, 10, 14, and 15 (Fig. 2). Data from this vicinity are plotted on a foliation-plane diagram (Fig. 3, No. 13), which shows a girdle with two well-developed maxima. Great circles having these maxima as their poles intersect at a point that is the local fold axis, $B_3$, about which the axial planes and limbs of the first and second folds have been rotated. This fold axis, $B_3$, plunges 70 degrees in the direction N71°E (071°/70°) and the concentration of the third lineations, plotted in the same diagram, coincides with this fold axis, $B_3$. Thus, these third folds plunge steeply down their axial planes, and, like the second folds, are inclined folds.

In the west and northwestern parts of the map-area the axial planes of the third folds (Nos. 16, 17, and 18, on Fig. 2) also trend N40°W, but the direction of dip is to the southwest at about 70 degrees. These third folds are superimposed upon first folds, whose limbs and axial planes have been refolded about an axis, $B_3$, that has a variable amount of plunge from 34 to 66 degrees in the direction N60°W (300°/34° to 66°). As this plunge is down the dip of the third axial planes, these too, are inclined folds.

*Third Axial-plane Cleavage* ($S_4$)

Within the areas affected by the third-fold movements, a cleavage parallel to the axial planes of the third major folds, $B_3$, is well developed. This has a reasonably constant trend (Fig. 6); near Mesa Lake it dips steeply to the northeast, whereas near Scraper Lake it dips to the southwest. As with the second axial-plane cleavage, this change in the direction of dip is along a north-south line that corresponds to the axial trace of first fold No. 4 (Fig. 2).

*Third Linear Structures* ($b_3$)

The trends of the third lineations (Fig. 5) exhibit variations in direction and amount of plunge. These are the result of varying intersections of the first- and second-fold limbs with the axial planes of the third folds, whose trend is constant. In the eastern part of the map-area the trend of the third lineations, $b_3$, is nearly constantly to the east, but with variable steep plunges. In the western part, however, the lineations, $b_3$, trend from southwesterly to westerly and also vary in their amount of plunge.

The limbs of second fold No. 7 (Fig. 2) exhibit slight warpings owing to the third-fold movements related to the development of third folds Nos. 11, 12, and 13 (Fig. 2). The great circle of foliation-plane poles, $S_1$, from subarea No. 11 of Figure 3 and the positions of the maxima contained within this girdle are shown on Figure 15. Great circles, whose poles correspond to these two girdle maxima, have been drawn on Figure 15; these represent the two limbs of second fold No. 7. The average axial plane of the third folds from the eastern part of the map-area intersects the two limbs at two points, which correspond to the plunges of the third lineations on the limbs of this second structure. On the west limb of the second structure the superimposed lineations plunge 70 degrees in the direction N59°E (059°/70°), whereas those on the southeast limb plunge 62 degrees in the direction S18°E (108°/62°).

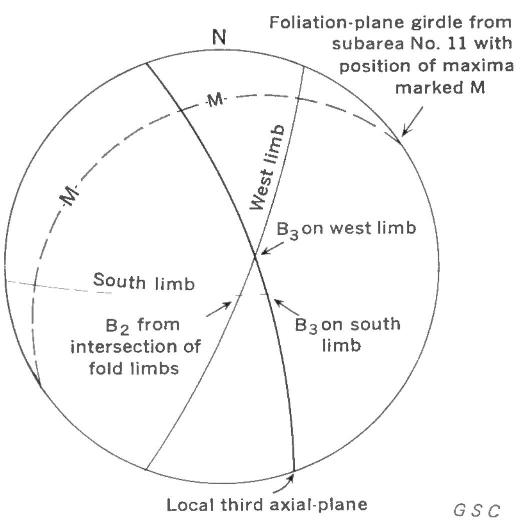



**FIGURE 15.** Calculated orientations of the third fold axes ($B_3$) on the south and west limbs of the second fold No. 7, in subarea 11.

A synoptic diagram (Fig. 16A) of all the plots of third lineations from all of the subareas east of fold trace No. 4 of Figure 2, shows that these lineations fall into two marked groups, which correspond to the calculated values of the third linear structures shown on Figure 15. Third lineations from the subareas west of the first fold trace No. 4 also fall into two groups that plunge westerly and southwesterly at about 50 and 75 degrees, respectively (*see* Fig. 16B).

A diagram showing the calculated values for the third linear structures west of fold trace No. 4, if constructed in a manner similar to that used for Figure 15, would show that these calculated values coincided with the two groups of third lineation plots in the synoptic diagram Figure 16B.

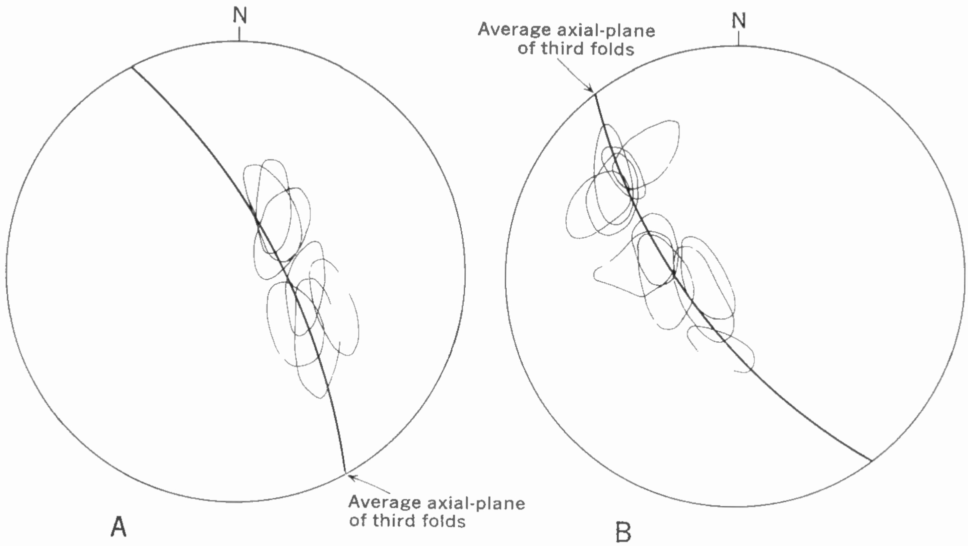



FIGURE 16. Composite diagrams of third lineation ($b_3$) fields from subareas east (A) and west (B) of first fold-trace No. 4.

### *Deformation of the First and Second Folds and Their Associated Minor Structures*

The third folds, which in places have been superimposed upon both first and second folds, for the most part resulted in intense deformation of these early structures, with their limbs and axial planes being refolded about new axes.

*Distortion of Major Folds ($B_1$ and $B_2$) by the Third Major Folds ($B_3$)*

Major distortion of early folds is recognizable near Mesa and Scraper Lakes, but minor warping about the third axes is present in adjoining areas, in the form of slight corrugations of the axial planes and limbs of the first and second folds. The axes about which this warping took place have variable directions and amounts of plunge, which are controlled by the attitude of the limbs of the first and second structures that have undergone refolding. Evidence of this slight refolding about the third axes is shown on Figure 3 (Nos. 1, 3, 4, 6, 8, 9, 11, 12, 14, and 15). The concentration of the plots of the third axes on these diagrams obviously bears no relation to the girdles of foliation-plane poles that were produced during the development of the first and second folds.

Evidence of the folding of both first and second major folds is present in subarea 12 (the location of which is shown on the insert map of Fig. 3) immediately north of Mesa Lake. There, first fold No. 2 (Fig. 2) and second fold

No. 9 were folded during the development of third fold No. 11, so that the first fold No. 2 has been involved in two deformations that are practically at right angles to each other (Fig. 17A and B). Excessive movement during the refolding about the third axis resulted in further closure of these first and second folds about their original axes, together with shearing parallel to the axial plane of the second fold No. 9. This shearing brought about the thickening and thinning of the hornblendic horizon at the northwest end of Mesa Lake, together with the development of fine-grained mylonitic rocks within the core of this second fold. Intense closure about this second fold axis, because of refolding about the third axis, has resulted in the mylonitic rocks being almost parallel to stratigraphic horizons related to first fold No. 2.

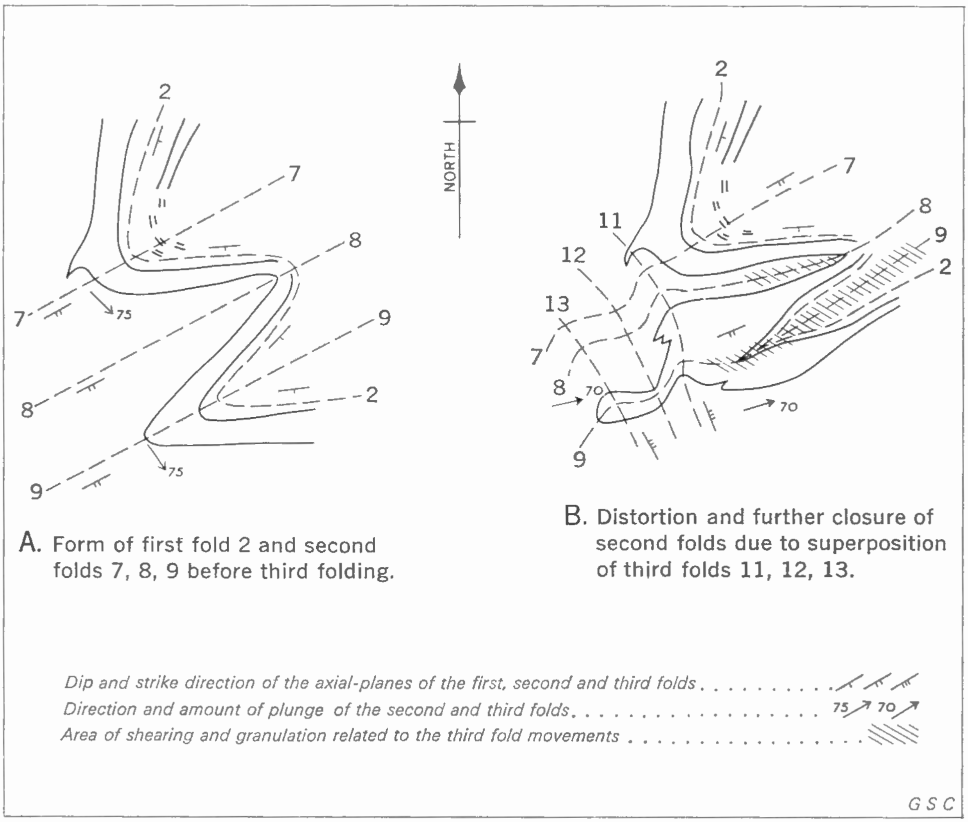



FIGURE 17. Refolding of first- and second-fold movements within subareas 12 and 13.

Third folds are also developed in the map-area near and south of Scraper Lake. These have not involved the intense deformation that is characteristic of those third folds developed near Mesa Lake; rather, they are gentle warpings of the earlier structures.

### *Distortion of Axial-plane Cleavages ($S_2$ and $S_3$) and Minor Folds by the Third-Fold Movements*

Southwest of Mesa Lake, the axial-plane cleavages related to the first and second folds have been almost obliterated by the intense deformation associated with the formation of the third folds. North of Mesa Lake, however, near Dune Lake and in the western part of the map-area, where the third-fold movements appear as gentle warpings of the earlier structures, the axial-plane cleavages have undergone rotation about the third fold axes in a manner similar to that of the limbs of the earlier fold structures. This rotation of the first and second axial-plane cleavages is plotted on Figure 6, and on Figure 4 (Nos. 2, 13, 16, and 17).

Minor folds that developed during the first and second periods of folding were deformed by rotation about the third axes of folding and show geometric differences, which were produced by differences in the intensity of the third deformation. This variation in geometric form is dependent upon the angular relation between the first- and second-fold limbs and the third axial planes. Examples of early minor folds deformed by rotation about the third fold axes are shown on Figure 18.

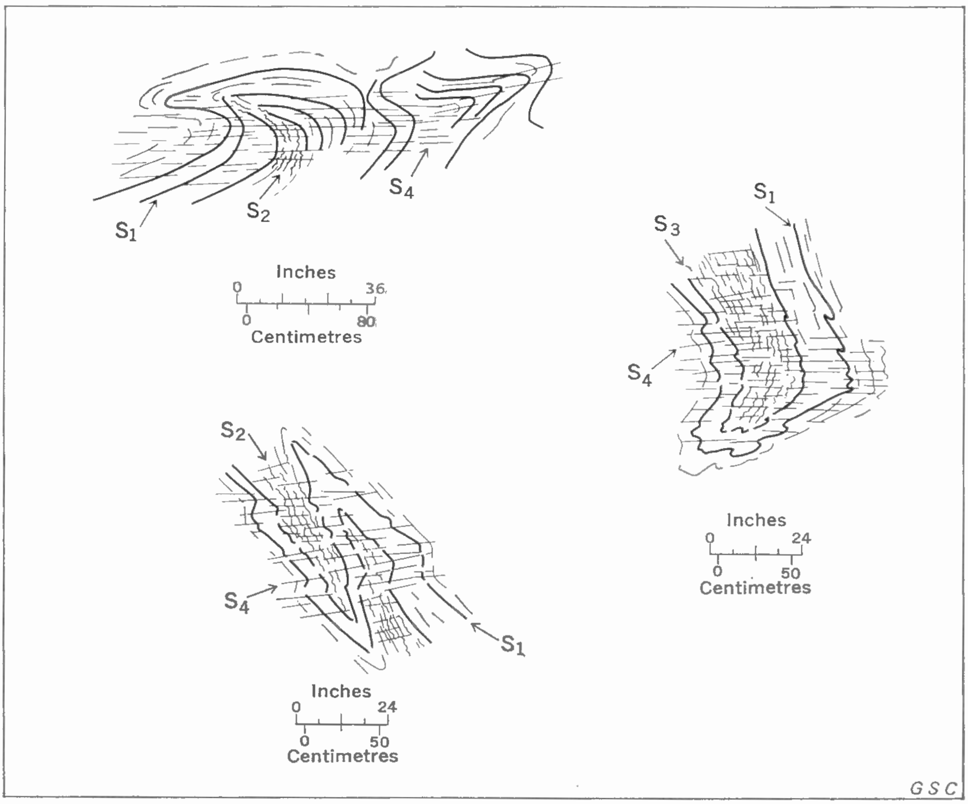
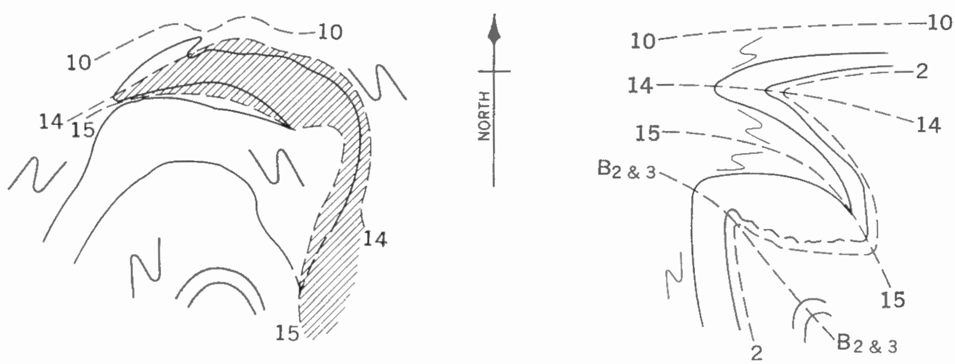



FIGURE 18. Field sketches of early minor folds deformed by third-fold movements.

The ground trace and sense of movement of minor folds were noted throughout the area mapped. Knowledge of the sense of movement of the early minor folds, despite their distortion by the third-fold movements, enables the complex structure at the southwestern end of Mesa Lake to be understood. Figure 19A shows the ground trace and sense of movement relations between the second and third minor folds. Figure 19B shows the outcrop pattern of the sense of movement of the second minor folds after rotation about the third axes has been accounted for. This latter diagram indicates the disposition of the second folds Nos. 14 and 15 prior to folding during the third-fold movements; these two folds (Nos. 14 and 15) are mirror images of the second folds Nos. 8 and 9 north of Mesa Lake. Thus the second folds Nos. 7, 8, 9, 14, and 15 are minor folds formed on the limbs of a major second fold, whose axial trace now trends nearly east-west and is shown on Figure 2 by fold trace No. 10; the geometric form of this major second fold is the same as that of the minor folds developed on its limbs.




A. Area where third minor folds show a sense of movement opposite to that of the second minor folds

B. Form of second folds 14, 15, $B_2$ before superposition of major third fold $B_3$

*Area* . . . . . . . . . . . . . . . . . . . . . .

*Ground trace of minor folds associated with the major third fold* $B_3$. . . . . . . .

*Ground trace of minor folds associated with the second folds* 14, 15, $B_2$ . . . .

GSC

FIGURE 19. Early minor folds deformed during the third-fold movements and the form of the southern limb of second fold No. 10.

*Distortion of the Early Lineations, $b_1$ and $b_2$, by the Third Fold Axes ($B_3$)*

The early linear structures were all deformed at the same time by rotation about the third fold axes, as were the axial planes and limbs of the folds to which these early linear structures were related (Fig. 5).

As an example of the rotation of early structures about the third axes, poles to foliation planes, $S_1$, in subarea 13, at the western end of Mesa Lake together with all the linear structures measured, are shown in Figure 3, No. 13. This diagram shows a well-developed girdle with two strong maxima. Great circles, whose poles correspond to these maxima, intersect at a point that represents the plunge of the local third fold axis, $B_3$, and this point coincides with the concentration of the third lineations measured within the subarea. The early linear structures related to the first and second folds are scattered about this concentration of third lineations and obviously bear no relation to the foliation-plane ($S_1$) girdle, which was formed during the third-fold movements.

## Summary of Structural Events

The structures of Mesa Lake map-area indicate that the rocks have undergone three periods of folding on different axes, with each fold system comprising major folds and associated minor structures. The earliest, first-fold movements gave rise to a series of anticlines and synclines whose axial planes were nearly vertical and had a fairly constant northerly trend. These folds were further closed about their originally southerly plunging axes, and were distorted by a second and third set of folds whose axial planes trend northeasterly and northwesterly, respectively, and whose associated minor structures are clearly separated in the field. The second and third folds are sideways closing folds whose geometry and direction and amount of plunge are controlled by the attitude of the limbs of the folds upon which they are superimposed.

In Mesa Lake map-area, evidences for the three periods of folding are readily recognized. The first-fold movements were confined to the Yellowknife Group, whereas the second- and third-fold movements affected both Snare and Yellowknife Groups. All fold movements were accompanied by regional metamorphism, local migmatization, and the formation of axial-plane cleavages and well-developed linear structures. The final stage of movements within the map-area, probably some considerable time after the cessation of the period of folding, gave rise to east-west tear faults.

# METAMORPHISM AND LATER GRANITE INTRUSIONS

Two main tectonic and metamorphic events have been deduced from the writer's study of the rocks within Mesa Lake map-area. They are separated by a period wherein the deformed Yellowknife Group rocks were eroded and later became covered with Snare Group sediments. These two periods of deformation took place entirely within Precambrian time and were accompanied by metamorphism.

A widespread metamorphism accompanied the deformation of the Yellowknife Group, raising the rocks to the greenschist facies, with mineralogical characteristics as described under *General Geology*.

After the deposition of the Snare Group sediments, a second and a third period of deformation affected the rocks of both the Snare and Yellowknife Groups, and sediments of both groups responded in varying degrees to metamorphism accompanying this deformation. Evidence of this metamorphism is the development of the mineral assemblages chlorite-sericite, biotite-cordierite, and biotite-cordierite-sillimanite. The last is commonly associated with migmatites and patches of porphyroblastic granite, with which it is unstable.

Metamorphism accompanying the deformation of the Yellowknife Group was of the lowest greenschist facies and was uniformly distributed. The later metamorphism, which accompanied the deformation of the Snare Group, was highly variable in distribution, and its effect upon the sediments of the Yellowknife and Snare Groups is described below.

Later, after the establishment of these new mineral assemblages, small bodies of granite were intruded into the already metamorphosed sediments. These granite bodies had little or no thermal effect on the country rocks, and commonly have marginal pegmatites associated with them.

## Mineralogical Changes Produced by the Metamorphism

Evidence can be found in the map-area of progressive metamorphism from rocks in the slate/phyllite grade through schists and gneisses to migmatites, the whole series being characterized, for the most part, by cordierite and aluminum silicates.

### Chlorite-Sericite Grade

The least altered sediments are characterized by the presence of chlorite and sericite, as already described.

Slates within this grade are phyllitic and are characterized by a very fine grained aggregate of chlorite and sericite, together with minor quartz and accessory opaque minerals. Subgreywackes are essentially of the same composition as the slates, but the minerals are present in different proportions, grains of quartz and plagioclase being set in a finer grained matrix of chlorite and sericite. The quartz-feldspar sandstones and quartz sandstones have micaceous minerals that commonly outline the bedding, and are a mixture of chlorite and sericite flakes.

Bands and nodules of calc-silicate granulites are ubiquitous and, throughout the area, are composed essentially of quartz, garnet, a lime-silicate, and one or two ferromagnesian minerals. Within this lowest grade of metamorphism, the stable assemblage present in these granulites is quartz, red-brown garnet, zoisite, and clinozoisite, sodic plagioclase, a blue-green hornblende, and minor chlorite and biotite.

The hornblendic rocks are composed of a fine-grained assemblage of hornblende and plagioclase, together with minor epidote. This appears to be the common assemblage for this map-area, regardless of what minerals are developed within the other rock types. The only effect of the metamorphism on these hornblendic rocks was to increase their grain size.

Limestone west of Mesa Lake lies wholly within this lowest grade of metamorphism.

### Biotite-Cordierite Grade

The change from the chlorite-sericite grade to rocks characterized by biotite-cordierite is a gradual one, and cannot be truly represented by a single isograd. Rather, the two grades are separated by a narrow transitional zone wherein biotite grows and appears to take the place of chlorite and sericite.

Pelitic rocks within this grade are biotite schists, and commonly exhibit small pink garnets together with small dark knots of cordierite up to 1 cm across.

Subgreywackes do not differ much from those of the chlorite-sericite zone. The grain size of the constituents is slightly increased, and grains of quartz and plagioclase are set in a matrix of biotite and muscovite flakes. Porphyroblasts of cordierite are also developed within the subgreywackes, but not nearly to the same extent as in the pelitic sediments. Graded units of subgreywacke and slate within this zone display an apparent inversion of tops of beds owing to the intense development of cordierite within the upper original slaty part of the unit as opposed to the sparse development of that mineral within the more arenaceous part.

Quartz-feldspar sandstones and quartz sandstones show a slight increase in grain size over their counterparts in the chlorite-sericite metamorphic zone, and the micaceous mineral present is a red-brown biotite. Porphyroblasts of cordierite and pink garnet are rarely found within these two rock types.

The calc-silicate granulites exhibit almost the same mineral assemblage as they do in the chlorite-sericite metamorphic zone, except for a slight change in the composition of the plagioclase to a more basic variety (intermediate andesine). Actinolitic amphibole, minor biotite, garnet, zoisite, and zoned plagioclase are set in a mosaic of granular quartz.

### Biotite-Cordierite-Sillimanite Grade

Included within this grade are coarse-grained schists and gneisses, the latter apparently derived from the former by the development of streaks and patches of quartzo-feldspathic material. The pelitic rocks of this grade are dominantly biotite-cordierite-sillimanite schists, which, with the development and increase in amount of quartzo-feldspathic material, pass into coarse gneisses. Their components are cordierite, quartz, oligoclase, microcline, pink garnet, and sillimanite set in a base of coarse flakes of red-brown biotite and rare muscovite. Sillimanite commonly occurs as dense masses of fibrolite, which seemingly grows at the expense of the biotite, and more rarely as good prismatic crystals. Porphyroblasts of small brown staurolite and pale pink andalusite are of sporadic occurrence.

Lenses and streaks within the gneisses are composed essentially of quartz and microcline, or of aggregates of ovoid grains of microcline with subordinate oligoclase. Subgreywackes at this metamorphic level are schistose mixtures of quartz, oligoclase, cordierite, sillimanite, rare pink garnet, and biotite. Quartz-feldspar sandstones and quartz sandstones are composed of a granulitic association of dominant quartz with microcline, oligoclase, biotite, and muscovite. Cordierite and garnet are scattered sporadically throughout these quartzose rocks.

Calc-silicate granulites within this zone show a marked change in their mineralogy. Poikilitic diopside has grown around and at the expense of the blue-green amphibole of the previous grade and the plagioclase feldspar has changed to a more basic variety (acid labradorite). Garnet and zoisite, together with sporadic flakes of red-brown biotite, are scattered through the rock, whose matrix is still composed of granular quartz.

### Migmatites

Within the northwestern corner of the map-area, west and north of Scraper Lake (Fig. 2), the metamorphosed sediments of the previous grade are intimately mixed with granitic material, resulting in the formation of coarse-grained banded and porphyroblastic gneisses, or migmatites. Associated with these migmatites are large patches of coarse, foliated porphyroblastic granite. Migmatites also occur in the southeastern corner of the map-area, south and east of Tropic Lake (Fig. 2), and pass westwards into strongly foliated biotite-gneiss.

The metamorphosed sediments involved in the formation of migmatites near Scraper Lake are the pelitic and more siliceous members of the succession. They are coarse-grained gneisses rich in feldspar and mica, and contain the following constituents, in order of abundance: microcline, oligoclase, biotite, quartz, cordierite, and subordinate garnet, sillimanite, and muscovite. Sillimanite is not abundant within these migmatitic rocks and, where seen, is always closely associated with small sericite flakes, which appear to be growing at the expense of the sillimanite. These gneissic rocks are well foliated with bands and streaks of orthoclase, oligoclase, and quartz paralleling the bedding ($S_1$). In the pelitic varieties large ovoids of orthoclase feldspar have grown in a groundmass of micaceous minerals. Gradations into these porphyroblastic and banded gneisses from the schists of the preceding grade are seen in a few places, and by increase in the number of porphyroblasts and grain size, the gneisses pass gradually into coarse patches of porphyroblastic granite.

The associated patches of coarse, foliated porphyroblastic granite vary in size and shape, but appear always to have their long directions directed nearly parallel to the strike of the composition banding (foliation plane $S_1$) of the gneisses. Porphyroblasts of orthoclase feldspar up to 1 inch long are oriented parallel to the third axial-plane cleavage ($S_4$), which is shown in these gneisses by the orientation of micas. As seen in thin section, these porphyroblasts display highly sutured margins and contain inclusions of the groundmass minerals quartz, oligoclase, and biotite.

Thin bands of calc-silicate granulites are found within the more siliceous gneisses. In these rocks the pyroxene of the previous grade appears unstable, for fibres of actinolite have grown along its cleavage directions. The plagioclase is reversely zoned and in places has small flakes of scapolite growing within its margins.

## Relation of the Metamorphism to the Deformation of the Snare Group

All the minerals produced by metamorphic recrystallization show a high degree of orientation. Micaceous minerals are commonly oriented and crumpled, especially in pelitic horizons where herring-bone cleavage is locally apparent. As seen in thin sections, each of the small crumples shows that the micas within the cores of corrugations are strained, whereas those on the crests are strain free.

Porphyroblastic minerals, too, show signs of orientation. Pink garnets show spiral growth; patches of fibrolite show S-shaped strains; cordierite grains are elongated and flattened so that they lie within cleavage planes, their long directions parallel to the local lineation; quartz rods and quartz-sillimanite knots are elongated parallel to local fold axes. All these features suggest that the metamorphism and deformation were contemporaneous.

In the southwestern and western parts of the map-area, where the three metamorphic assemblages are well developed, the second and third linear structures are extremely well displayed in the elongation and orientation of metamorphic minerals, especially quartz-sillimanite knots. However, within the migmatites, north and west of Scraper Lake, the second structures appear to be overprinted by the metamorphic minerals and only the third structures are evident. Thus, it would seem that the metamorphic zones were established before the onset of migmatization, which was superimposed upon the highest grade of metamorphism. This suggestion is borne out by the fact that the metamorphic assemblages within the migmatites are unstable, in that sillimanite is reduced to sericite, and diopside has actinolite along its cleavage directions.

The presence of sillimanite and cordierite, the so-called "anti-stress" minerals, implies a high temperature and a relatively low degree of shearing stress. On the other hand, the high degree of orientation of sillimanite and other metamorphic minerals suggests that the shearing stresses were not too low. The intensity of deformation in the western part of the map-area, where the metamorphic zones are well developed, was low compared to that near Mesa Lake to the east.

The zones of metamorphism and migmatization are parallel to the margins of a large body of granite/granodiorite that lies west of Mesa Lake map-area and was emplaced wholly within rocks of the Snare Group. The emplacement of this granitic body and the concomitant development of a migmatitic/metamorphic thermal aureole may have been effected in part contemporaneously with the deformation of the Snare and Yellowknife Groups, which gave rise to the second- and third-fold systems.

## The Late Granite Intrusions

Later than the metamorphism but before the faulting, several small bodies of granite were intruded into the country rocks of Mesa Lake map-area. These intrusive bodies can be separated into two groups, the white granites and the pink granites, the pink probably being the younger.

Two fairly large bodies of white granite lie within the map-area. Both are foliated, even, fine-grained granites having tourmaline as a common accessory mineral. Their contacts with the country rocks are sharp, but they have a marginal zone of inclusions, normally about 200 feet wide, in which the inclusions are commonly angular, showing little or no sign of digestion by the granite. Thermal alteration of country rock by the white granite is slight. Large poikilitic plates of biotite and needles of tourmaline, having a mimetic orientation, occur within the country rocks for a distance of some 300 feet from the contact. Small bodies of simple pegmatites are also associated with these granite bodies and can be considered as marginal effects of them. These pegmatites, which are composed of quartz, orthoclase, muscovite, biotite, and tourmaline, occur near and within the zone of thermal alteration and are chilled against the country rocks.

Probably intrusive into the country rocks later than the white granites, are small bodies of an unfoliated, pink granite (microgranite). These rocks are exposed near the northern reaches of Emile River, where one has been displaced by a late tear fault. Their mineralogy is simple–pink orthoclase, quartz, and biotite. Tourmaline is absent, as are marginal zones of inclusions and thermal alteration of the country rocks.

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