PROGRESSIVE STRUCTURAL REWORKING OF THE UIVAK GNEISSES, JERUSALEM HARBOUR, NORTHERN LABRADOR

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BY

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ABSTRACT

The region around Jerusalem Harbour in northern Labrador is composed of a suite of metamorphic rocks of various ages and origins. The Uivak gneisses, containing Saglek dyke and pre-Uivak inclusions, are the deformed and metamorphosed equivalents of an igneous suite emplaced into the crust over 3.6 b.y. ago. Tectonically intercalated with the Uivak gneisses are belts of metasedimentary and basic gneisses known as the Upernavik supracrustals.

Both the Uivak gneisses and Upernavik supracrustals have been variably migmatized during a period of crustal instability manifested by metamorphism and deformation 3.1 b.y. ago. This 3.1 b.y. event was marked by the generation of a new series of gneisses, herein termed the Iterungnek gneisses. These younger tectonites are a composite, heterogeneous, suite derived both from the remobilization of the earlier Uivak gneisses through a mechanism of structural and metamorphic reconstitution and <u>in situ</u> anatexis, and synkinematic granitic intrusions. In areas where structural reworking has been dominant, the Uivak gneisses can be shown to have undergone progressive transposition until the earlier layering has been completely reoriented and gradually obliterated at the expense of the imposed (Iterungnek) foliation. Where anatexis has been the dominant mechanism, the gneisses show a gradation from lit-par-lit

migmatites with Uivak characteristics into Iterungnek nebulites having a granular aspect. The rejuvenation of the Uivak gneisses was synchronous with the intrusion of weakly foliated granitic bodies which gave rise to megascopic agmatite zones where they were emplaced into or adjacent to the Upernavik supracrustals.

Detailed petrological studies of all the major rock units in the area has shown that the reworking of the Uivak gneisses occurred under granulite facies conditions, which were superimposed on rocks with upper amphibolite facies assemblages. Mineral reactions observed in thin section indicate P-T conditions for the granulite metamorphism to be in the range of 10 kb and 825-850°C, implying a crustal thickness 3.1 b.y. ago on the order of 30 km.

Regional folds produced during the Iterungnek event are dominantly isoclinal about moderately plunging axes and nearly vertical axial planes. Mesoscopic structures indicate that shearing along the axial planes of tight folds of Uivak gneisses was an active mechanism in the production of the Iterungnek banding. The regional distribution of rock-types is suggestive of refoliation of the Uivak gneisses in synformal zones which have been "pinched - in" between more stable border massifs in which little reworking of the older gneiss is evident. It is postulated that this pattern resulted from "collapse" of the crust 3.1 b.y. ago along narrow parallel shear zones due to a softening effect from the build-up of radiogenic heat.

Even though initial Sr ratios from reworked gneisses in Labrador agree with present theories on Sr systematics in crustal rocks, such is not the case in Greenland. It is suggested that more research is needed into such areas of reconstituted early Archean sialic crust like that in Labrador in order to reconcile the inconsistencies between the observations of the field geologists on one hand and the isotope geologists on the other.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the help of the following people who have contributed to this thesis, either directly or indirectly. Without them this study could not have attained its present form.

Ian Knight of the Newfoundland Department of Mines and Energy introduced me to the splendid scenery and fascinating geology of northern Labrador in the summer of 1972, and sparked my initial curiosity about the development of the Archean rocks of that area. The opportunity to study these rocks in more detail was provided by Dr. K.D. Collerson of Memorial University, my supervisor in this project. His comments and discussions of various aspects of the geology of the Saglek area during the writing of this thesis has helped to clarify portions of the discussion, and he reviewed the final manuscript prior to submission.

Geoff Martin was my cheerful and helpful assistant during the field part of the study. He provided the necessary conversation to while away the time over innumerable mugs of tea when the fog, wind, and rain had us camp-bound for days on end. The descriptions of the ultramafic rocks presented herein have been augmented by the work of Martin, who studied them as part of an honors dissertation project.

Dr. R. K. Stevens (M.U.N.) pointed out Bailey's book on the Alpine System to me, in which the account of Jurassic fossils in metamorphic rocks is presented. Dr. M.J. Kennedy (now at Brock University) discussed several aspects of the general structural geology with me, and his undergraduate and graduate courses in structure while at M.U.N. helped me to understand processes of rock deformation in relation to the principles presented by Flinn and Ramsay.

I would like to thank F. Thornhill, L. Warford and J. Ford for making the thin sections, sometimes on very short notice, and W. Marsh for the photographic prints used in this thesis.

The final manuscript was typed by Miss Elaine Boone of M.U.N. Mathematics Department. Her capable handling of the unfamiliar geological jargon is to be commended. Debbie Ryan is thanked for her patience and understanding during the long months of preparation of the thesis, and for her help with the drafting of the text-figures and preparation of the plates.

Friendly discussions with other geologists concerned with Archean crustal development have given me a better appreciation for geological processes in the early earth, especially V.R. McGregor, D. Bridgwater, J. Myers, J. Watson, W. Jesseau and R. McNutt. My attendance at the "Early Earth" conference in Leicester in April 1975 due to the kind efforts of B. Windley and support of NATO broadened my knowledge of crustal development in other shield areas.

My field expenses in northern Labrador during the project were covered by a National Research Council of Canada grant (Grant No. 8694) to Dr. K.D. Collerson. The bulk of the financial support for me while in residence at M.U.N. was provided by a Provincial Government Fellowship, augmented by funds from a central account formed by the faculty of the Geology Department from their research grants. All are gratefully appreciated.

FRONTISPIECE QUOTATION

"The Labrador Coast is still one of the most bold and rugged in the whole world ... . The bareness of the rocks, their freedom from obscuring forest and turf, helps the long coast to tell its own geological story. Mother Nature has there taken off more than the usual amount of clothing which she is wont to bestow on the land elsewhere; and the autographed story of the ages is so imprinted on her naked bones that those who run may read its thrilling pages, and the wayfaring man can enjoy the conceit of being for a while a veritable Sherlock Holmes. To know Labrador is to know her geology. Seldom elsewhere is the explorer's mind so forced to think to the very beginning of things. One day the scientific study of Labrador will bring a rich store to our knowledge of the whole earth."

from "The Romance of Labrador"
Sir Wilfred Grenfell, 1934

TABLE OF CONTENTS

LIST OF FIGURES

MAPS

The following maps are found in the pocket at the end of the thesis:

a) Geological map of the thesis area
b) Sketch-map showing detail of the geology on the west shore of Jerusalem Harbour

LIST OF PLATES

LIST OF ABBREVIATIONS

The following abbreviations are used to designate minerals shown in plates of photomicrographs

act - actinolite

bi - biotite [Bi(U) = Uivak biotite, Bi(I) = Iterungnek biotite, when shown]

cd - cordierite

chl - chlorite

cpx - clinopyroxene

fh - ferrohastingsite

hb - hornblende

m - muscovite

mt - magnetite

opx - orthopyroxene

pl - plagioclase

qtz - quartz

s - sillimanite

CHAPTER I

INTRODUCTION

I.1. Preamble: Polycyclic Gneiss Complexes.

Precambrian crystalline basements of metamorphic rocks have always been considered to be an entity vastly different from the younger sedimentary and volcanic successions which overlie them. They were long considered to have evolved under geological conditions which existed only at that specific time in earth history, and consequently all metamorphic rocks of this type were considered to be "fundamental complexes" or primitive crust of the Earth. Such views were held by Giovanni Arduino in 1759 with regards to the Alpine schists, by Abraham Werner in 1787 for all schists and granites, by Adam Sedgwick in 1835 for the pre-Paleozoic rocks of Wales, and by Sir William Logan in 1842, for the metamorphic rocks around the Great Lakes of Canada (see Geikie, 1962). It was not until the discovery of Jurassic belemnites in schists of the Alpine system by Albert Heim in 1888 that it was realized that metamorphic rocks were not restricted to the Precambrian.[1]

At the turn of the century Lyell's principles of uniformitarianism were applied to a sequence of metamorphic rocks in the Fennoscandian Shield by J. J. Sederholm. He

[1] A fascinating account of the controversy arising from this discovery can be found in Bailey (1968, p.104-28)

interpreted metasedimentary and meta-volcanic rocks in this region to have been initially derived by processes similar to younger rocks, having attained their present form from widespread pervasive metamorphism and deformation. Later Wegmann (1929) applied procedures utilized in Alpine structural studies to Precambrian tectonics, showing that basement/cover deformational styles were interrelated, the Alpine type structures being the higher level manifestations of more complex structures in the crystalline basement at depth.

Once these principles and observations found acceptance in the geological community, investigations began to show that the complex structural histories exhibited by many Precambrian basement gneiss terranes could be unravelled by the successful demonstration of the superposition of several distinct folding and metamorphic episodes. From such studies developed the foundations of structural geology, brought to the forefront by Bruno Sander in 1930 with his classic Gefügekunde der Gesteine, which was introduced to English-speaking geologists by Knopf (1933). One pioneer study involving the application of Sander's principles was that of Weiss (1958) during a structural investigation of the basement gneisses at Turoka, Kenya. During the 1960's the application of structural geology in elucidating the evolution of polydeformed regions became more widely employed because of the theoretical and field-oriented discussions of Wilson (1961), Flinn (1962), Turner and Weiss (1963) and Ramsay (1967). An important observation arising from such studies was the recognition that re-deformed or polycyclic gneiss complexes commonly exhibit only the effects of the most intense deformation(s) which may or may not obliterate all evidence of earlier structures. Such features have been admirably demonstrated from gneiss complexes in Scotland (eg. Sutton and Watson, 1951; Myers, 1970; Coward, 1973 a, b,), Greenland (Berthelsen, 1957, 1960; Windley, 1966; Watterson, 1968), and the Pyrenees (Zwart, 1960) to mention a few. From these studies there has arisen a number of criteria which may be used to access the processes by which polycyclic terranes evolve. The mechanisms of re-deforming and reconstituting previously gneissose regional metamorphic rocks has recently been put into a crustal context by Watson (1973).

The purpose of this thesis is to describe an area of Archean gneisses in northern Labrador, Canada, which shows evidence of polycyclic evolution, and to discuss some aspects of the deformation by which an early series of quartzo-feldspathic gneisses is refoliated and transposed by widespread reworking. The term reworking is used in the sense of Watson (op. cit., p.455) to mean the "reconstitution of older crystalline rocks within the crust .... by deformation in association with metamorphism and, on occasion, with partial melting or introduction of granitic material."

I.2. Location of Thesis Area.

The area studied is located at the southern extremity of the Torngat Mountains on the northeast coast of Labrador, and consists of a peninsula bounded by Hebron Fiord (58°10'N) to the south, Iterungnek Fiord (58°15'N) to the north, and the Labrador Sea (Atlantic Ocean) to the east (Figure 1). No inhabitated settlements occur within the map area; the abandoned Eskimo village of Hebron is situated in the south, on the fiord of the same name. Hebron was founded by the Moravian missionaries in 1830, but because of its remote location was abandoned under the Newfoundland Provincial Government resettlement program during 1959-60 and its Eskimo inhabitants were moved south to Nain, Hopedale and Makkovik.

I.3. Field Work in Northern Labrador.

The remoteness of the northern Labrador coast makes access to it a major problem. Individuals engaged in any form of activity in the far northern part have to depend heavily on chartered aircraft for transportation to and from the region. However access by boat becomes feasible following the spring break-up of the winter Arctic ice-pack.

The geological team of which the writer was a member gained access to the field on July 7, 1975, by charter flight on a twin-engine Otter of Labrador Airways from Goose Bay to the International Telephone and Telegraph (IT & T)

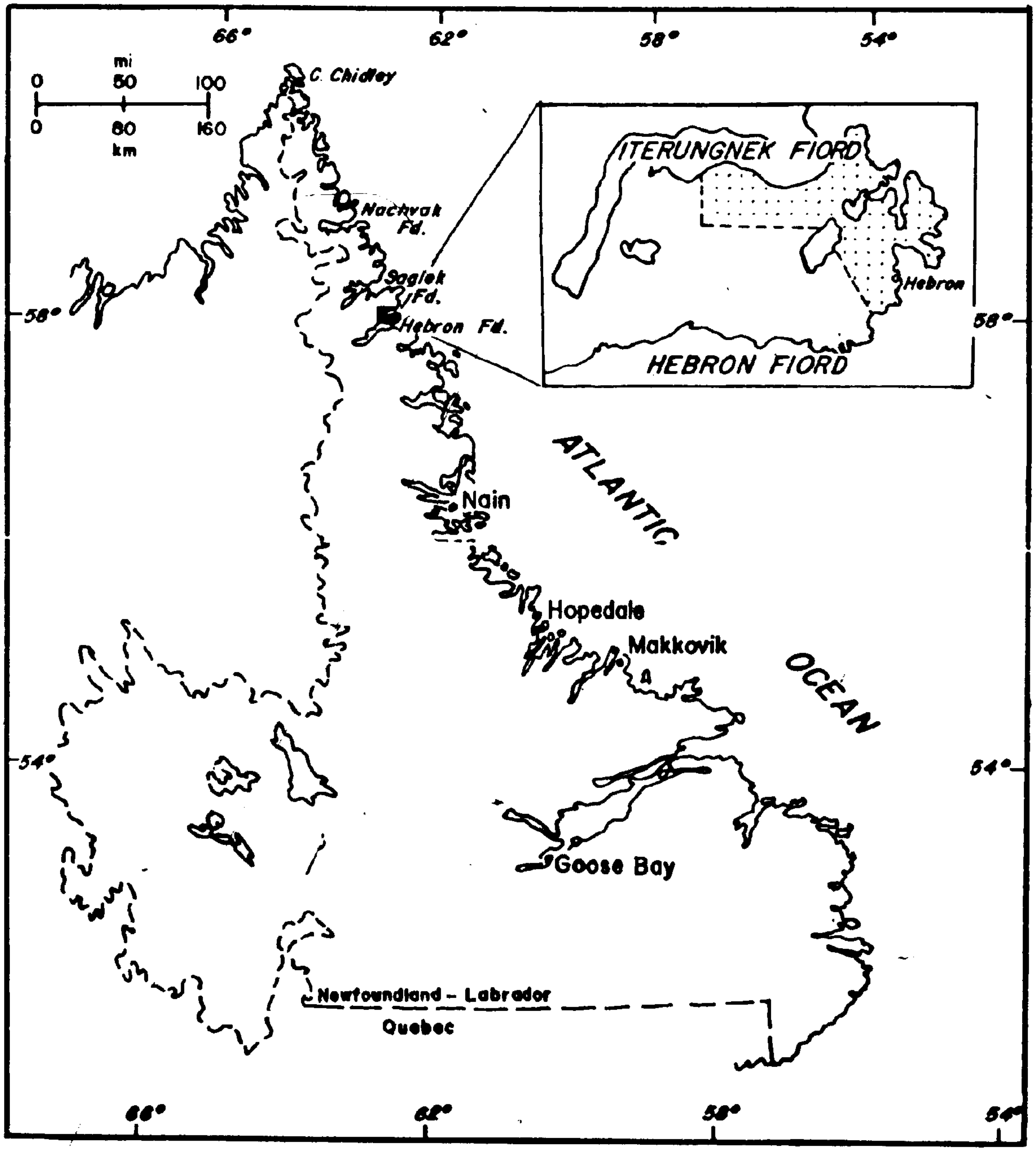

Figure 1. Location of the study-area on the northern coast of Labrador. Dotted pattern on insert shows area described in this thesis.

communications installation on the United States Airforce BMEWS (Ballistic Missile Early Warning System) site at Saglek. Field equipment was transported from Saglek to a base camp at the head of St. John's Harbour, 12 km to the west, by two 17ft. (5.5m) Zodiac inflatable boats. On July 18, the writer and his assistant Geoff Martin set out from St. John's Harbour by rubber boat to the study area, accompanied in a second craft by Dr. K. D. Collerson and Mr. Robert Vocke. A field camp was set up in a small sheltered cove on Jerusalem Harbour 50 km due south of Saglek.

I.4. Physiography, Vegetation and Exposure.

The map-area is situated at the southern-most tip of the Torngat Mountains, a range of rugged peaks which stretch for 250 km from Hebron to Cape Chidley on the northern Labrador coast (Figure 1). Maximum elevations are on the order of 1800 m, these being found in the central and northern parts of the chain. No extreme heights are present in the map-area; rounded hills generally reach 250-350 m. Mt. Johannesberg, just outside the study area, is approximately 700 m, the highest point in this part of the Torngats.

The topography has been noticably affected by the glacial activity of the Pleistocene. Hills are rounded, polished, and in many places display a roche moutonnée form.

A broad U-shaped valley trending northeast across the map-area and forming the western arm of Jerusalem Hr. owes its form to glacial sculpturing. A large lake occupies a glacial depression in this valley. The narrow strip of land separating Jerusalem Hr. from Hebron Fiord is a raised wave-cut terrace, suggesting that Mt. Jerusalem itself was an island in early post-glacial time. Remnants of raised beaches several metres above present high-tide mark, also attest to higher sea levels and/or isostatic rebound of the region following de-glaciation.

The map-area lies north of the treeline (as defined on government forest inventory maps) which passes East-West through Hebron Fiord. No coniferous or large decidious trees are found in this area; the most common type of vegetation is the low-lying Arctic willow.

The lack of vegetation and glacial debris leads to widespread exposures of the bedrock, and ∿90% of the area exhibits such exposure. Unfortunately inland outcrops are cloaked with lichens which often makes subtle changes in lithology difficult to detect. Shoreline exposures however, annually scoured by the southward moving Arctic ice-pack, offer a great source of information, and most of the data presented herein have been gleaned from such areas.

CHAPTER II

THE GEOLOGY OF NORTHERN LABRADOR

II.1. Geological Setting.

The Labrador peninsula forms the greatest exposed area, and the eastern most extension, of the Precambrian Shield of North America in Eastern Canada. It is dominated by crystalline igneous and metamorphic rocks with local regions of mildly deformed sedimentary/volcanic cover sequences (Figure 2).

It was recognized by Wilson (1939) and Gill (1949) that the vast region covered by the Canadian Shield could be broken down into a series of structural divisions or provinces based on the general trend of rock units within the complex, possibly indicative of different orogenic periods during its geologic evolution.

The advent of isotopic dating by the Geological Survey of Canada (GSC) in the 1960's, made it apparent that there was a great diversity in ages within various parts of the Shield, but overlap in broad regions formed distinct clusters. These groupings of ages, seemed to indicate distinct orogenic episodes within the Precambrian, and led Stockwell (1961) to propose a preliminary time-stratigraphic division of the Shield (Figure 3). These isotopic age determinations augmented the earlier structural divisions. Seven provinces and several sub-provinces were defined to cover the Canadian

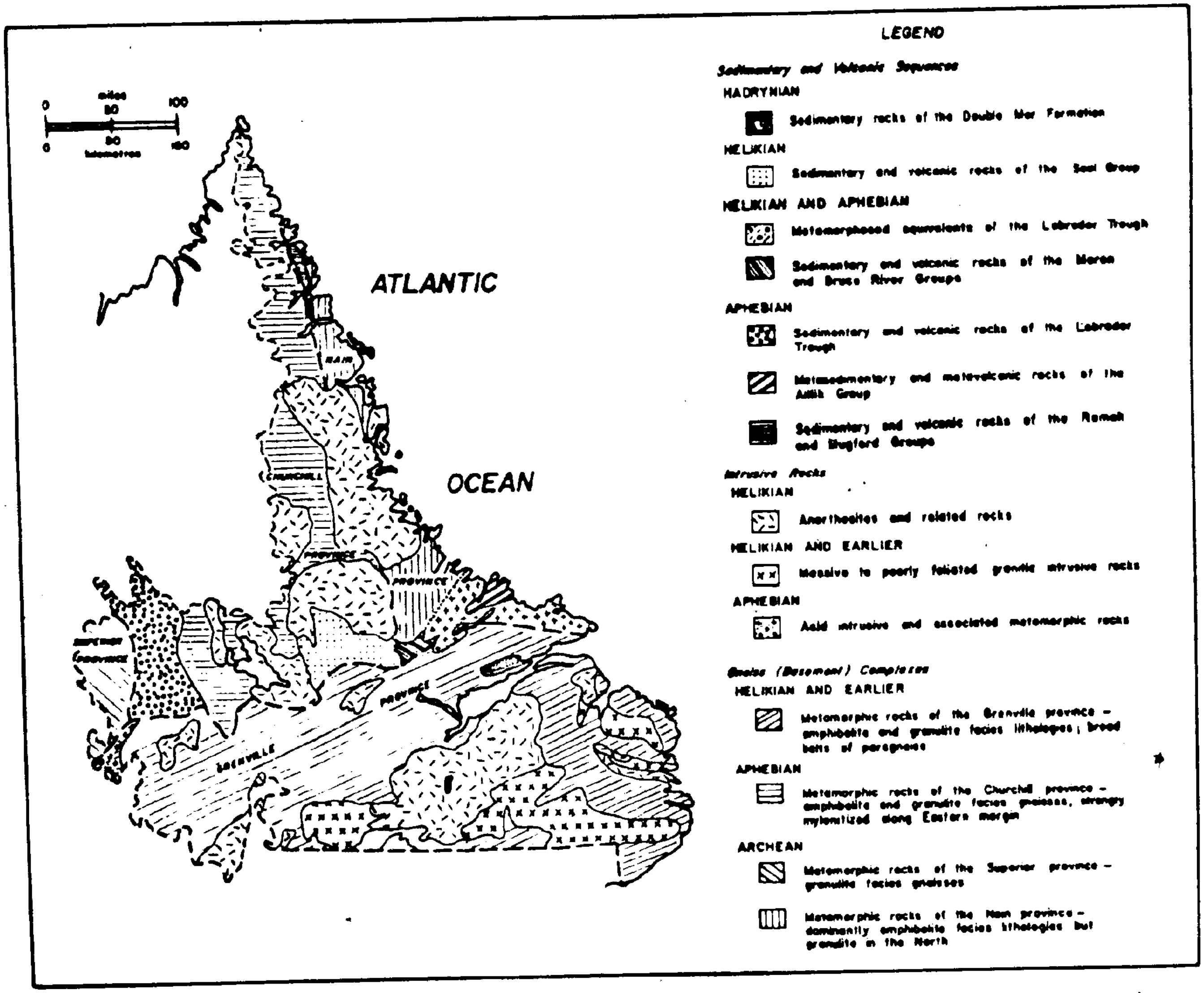

Figure 2. Geological map of Labrador (after Greene, 1974 with modifications from Smyth, Marten and Ryan, 1975; and Morgan 1975).

Eon	Era	Sub-era	Orogeny
PROTEROZOIC	Hadrynian		
	Helikian	Neohelikian	Grenvillian (955)
		Paleohelikian	Elsonian (1370)
	Aphebian		Hudsonian (1735)
ARCHEAN			Kenoran (2480)

Figure 3. Time-stratigraphic classification table for the Canadian Precambrian Shield (from Stockwell et al., 1970, p.51). Numbers in parentheses following the orogenies refer to the mean k-Ar mica age in millions of years.

Note: Most geologists now agree that the "Elsonian cluster", which applied to Labrador, can be attributed to widespread heating of the crust in this region during anorogenic intrusion of the anorthosite-adamellite plutons. It is probably better to think of the Elsonian as an "event" than to consider it an "orogeny" in the strict sense of the word.

continental Precambrian nucleus.

Stockwell (1963) recognized four geological provinces in Labrador - the Superior (Archean), Nain (Archean), Churchill (Middle Proterozoic), and Grenville (Upper Proterozoic), an observation which was a major contribution to the understanding of the geological evolution of Labrador. He later subdivided the Nain Province into Eastern and Western Nain sub-provinces (Stockwell, 1965). Reconnaissance mapping of Labrador by the GSC in the late 1960's and early 1970's led Taylor (1971) to (i) redefine the boundary between the Nain and Churchill provinces, (ii) to propose that the subdivision be dropped and the Western Nain be included in the Churchill and the Eastern Nain sub-province be raised to structural province status (retained as Nain), and (iii) that a narrow wedge of the redefined Nain composed largely of the Aillik (meta) sedimentary and (meta) volcanic rocks be designated as the Makkovik sub-province. The structural framework (Figure 4) outlined by Stockwell and Taylor is currently employed by geologists working in Labrador, although Taylor's nomenclature has sparked some discussion of its validity (Douglas, 1972).

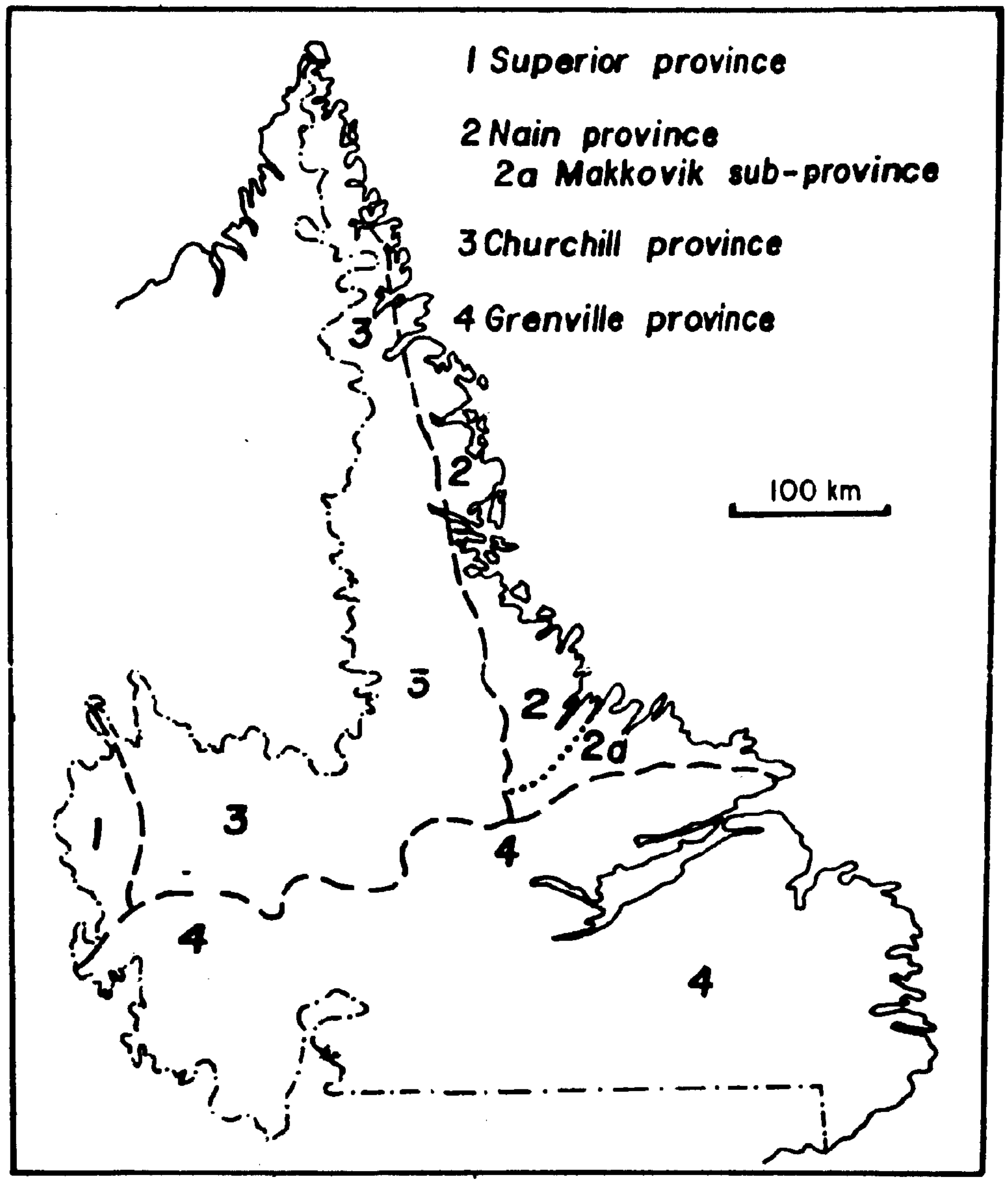

Figure 4. Distribution of structural provinces of the Canadian Shield in Labrador (from Greene, 1974).

II.2. History of Early Geological Investigations of Northern Labrador.

The forbidding nature of Labrador north of Nain and the difficulty of accessability has resulted in the geological investigations of this area being somewhat backward. The early reports of the geology are largely of reconnaissance nature, but several important geological relationships were observed.

The first mention of the rocks of northern Labrador appears to be in the account of two missionaries Benjamin Kohlmeister and George Kmoch who made an overland journey from Okhakh to Ungava in 1811. They observed that the rocks were dominantly grey, but streaked with black layers; slates and soapstone were encountered at several places on the trip (Kohlmeister and Kmoch, 1814).

Robert Bell was one of the earliest geologists to report on the bedrock geology of northern Labrador. He noted that the rocks were similar to the Laurentian of Ontario, being "micaceous and hornblendic schists and bedded gneiss" (Bell, 1884, p 14).

Professor E. B. Delebarre trekked overland from Hebron to Nachvak in 1900, and reported gneisses and slaty rocks near Ramah Bay (Delebarre, 1902).

The famous igneous petrologist of the early twentieth century, Reginald Daly was by far the most important contributor to the early geological investigations of northern Labrador. He observed that the "crystalline schists" of the ancient Basement complex at Hebron were "common biotite gneiss and amphibolite intersected by trap dikes" (Daly, 1902, p.225). The metamorphic rocks between Saglek and Nachvak were seen to be similar to this, but at Nachvak he encountered "coarse, friable, hornblende gneiss with abundant lens of segregated hornblende and biotite" (op cit , p.234) with cross-cutting sheets of purple-grey rock similar to the anorthosites and gabbros of Nain. He also noted the presence of ferruginous and siliceous schists, graphite gneiss, and "a peculiar breccia of angular quartz fragments embedded in a black corneous matrix" at Nachvak. Daly proposed the names Ramah and Mugford series for the volcanic/sedimentary successions of the Torngat and Kaumajet Mountains respectively, and noted their unconformable relationship to the gneisses. He also interpreted the "Nain gabbros" as being younger than the surrounding gneisses, and commented on the abundance of "trap" dikes cutting the old basement rocks.

Coleman (1921) summarized and extended the known geological knowledge of northern Labrador at the end of the second decade of this century. His observations and conclusions are interesting in light of recent work. He considered that the (Laurentian) quartzofeldspathic gneisses were largely derived from igneous parentage and proposed that many of the amphibolite bands in the gneisses were older than the surrounding granitoids, and should be classed as equivalents of the Kewatin of Ontario. Metasedimentary rocks associated with the gneisses were considered by Coleman to be possibly equivalent to the Grenville Series of Ontario, a view held widely by other geologists of this time. He seems to be the first to note that none of the numerous diabase dikes cutting the gneisses continued up into the overlying Ramah or Mugford cover successions.

Coleman observed granitic gneisses with discordant pegmatites cut by later diabase dikes at Saglek, and near Hebron he noted that the rocks were "grey igneous gneisses streaked with green schist". He postulated that a "wide belt of rusty weathering rock" behind the mission house at Hebron were of sedimentary origin (op. cit., p.45).

Odell (1938) made observations on the geology of the northern part of Labrador, as a member of the Forbes-Grenfell expedition there in 1931. He noted pyroxene and hornblende bearing gneisses at Nachvak, as well as areas of hypersthenite and charnockite. He described a 'pseudotachylite" veined rock from the same area, probably equivalent to the "peculiar breccia" noted earlier by Daly.

One of the most detailed early studies done on the gneisses of coastal Labrador was that of Kranck (1939a) who attempted to subdivide them into broad groups. He proposed the name

Domino gneiss [as used by Leiber (1860)] to include those basement rocks from Domino Run in southern Labrador north to Hopedale; the gneissose rocks from Hopedale to Hebron he termed the Hopedale gneiss. The latter he described as being a migmatitic microcline-rich granitic gneiss characterized by inclusions of "greenstone and skarn-like lime-rich schists" north of Nain (Kranck, 1939a, p.4).

Kranck (op. cit. p.28) also presented a tentative history of intrusion and deformation for the coastal belt. He believed that the gneisses were variably granitized equivalents of the Aillik meta sediments, those from Domino Run to Hopedale having been dominantly sandstone, while those of the northern coast formed from lime-rich and alumina-rich protoliths. Basic and ultrabasic rock types in the gneisses were postulated to have been derived from intrusives into the sedimentary pile. Kranck proposed that the term "Labradorian folding" be used to designate the orogenic phase which produced the observed gneissic layering, but pointed out that this overprinted structures of a still older orogen.

Tanner (1944) prepared an exhaustive treatise on the people, customs and natural history of Labrador in which he examined some aspects of the geology. He classified the coastal gneisses as being migmatitic grey gneisses, amphibolites and vein gneisses transected by pegmatites within which were belts of metasedimentary and metavolcanic rocks.

He noted that the metamorphic rocks of the northern Torngats were pyroxene granulites, often rich in garnet. Like Kranck, he postulated that the gneisses were largely granitized sediments because rafts of metasedimentary gneiss could still be recognized within them. Tanner considered that the original sedimentary pile was downwarped into the crust during orogenic compression. The level in the crust that these sediments reached dictated whether they were "remelted or changed by stress and metasomatic processes" into mineralogically banded rocks (Tanner, 1944, p.86). The zone of granitization, or migmatite front, migrated upwards, and he believed that the different gneiss types found on the coast of Labrador corresponded to erosional levels exposing different depths in the old mountain chain which the orogenic stresses had produced.

Christie (1952) also studied the coastal gneisses and divided them into granitoid, intermediate and metasedimentary gneisses. From Hebron, north to Nachvak he described highly garnetiferous light colored, strongly foliated granulites, whose association with recrystallized quartzites and carbonates suggested sedimentary protoliths. The gneisses at Saglek were described as a series of intermediate, brown-weathering, banded rocks locally rich in pyroxene.

Douglas (1953) visited several areas of gneissose rocks between Hebron and Nachvak during his evaluation of the economic potential of the coast during 1946-47. He sampled pyritiferous gneisses at Hebron and graphite bearing garnet-biotite gneisses at Saglek. North of Saglek he observed medium-grained greenish white gneisses and dark colored migmatites, both of which he believed were sediments "prior to granitization.".

In the 1960's the GSC isotopic dating program contributed greatly to the interpretation of the regional geology of Labrador, as outlined previously, and the recognition of Precambrian metamorphic rocks ranging from >2500 million to <1000 million years old was a major breakthrough from this era of geological investigation in Labrador.

The reconnaissance mapping of Taylor (1970) did little to contribute to the knowledge of the Archean rocks of northern Labrador. He saw the gneisses as "a great diversity of rock types" which could be described collectively as migmatites whose leucocratic components were granodioritic, aplitic and pegmatitic, containing hornblende, biotite and locally, pyroxene and muscovite. Amphibolites, rarely garnetiferous, thought to be derived from igneous and sedimentary parentage made up half of the foliated rocks in some regions. Quartzo-feldspathic granulites were found to be abundant in the northern part of the Archean terrane. Other rock types delineated by Taylor's broad-scale mapping included metasedimentary gneisses (lime silicates, quartzites) and ultramafic bodies.

In a recent publication, Morgan (1975) has reported on field work carried out in northern Labrador in the summers of 1971 and 1972, and has presented descriptions of the gneisses between Saglek and Nachvak fiords, rocks which form the peneplane unconformably beneath the Ramah Group. Although he has defined several distinct gneiss types, no details are given of the relationships between them.

East of the Ramah Group the rocks have been mapped as acid gneiss, banded gneiss, migmatite and granulite, with thin units and inclusions of basic gneiss, paragneiss, calc silicate and ultramafic rock. The mineralogy of the rocks indicates a granulite facies assemblage which has been largely affected by an amphibolite facies retrogression.

Morgan (op. cit.) has described the acid gneiss as a "fairly homogeneous" rock of granitic to granodioritic composition, cut by numerous granite and pegmatite sheets of several ages. Migmatization has led to "chaotic" minor structures in the gneiss. The acid gneiss and migmatites locally grade into paragneiss, thus leading Morgan to postulate that they (acid gneiss and migmatites) may be sedimentary derivatives.

Pyroxene-bearing hornblende gneisses and amphibolites were delineated as mappable horizons in several areas of the pre-Ramah complex. The basic gneisses locally have associated paragneiss and ultramafic rocks. Paragneiss also forms thick mappable bands intercalated with the other gneisses. The metasediments have a varied composition (pelite, quartzite, iron-formation) and are considerably migmatized.

Metamorphosed ultramafic rocks were found to occur scattered throughout the area, as conformable lenticular pods up to 2km long within leucocratic and basic gneisses. On the south shore of Nachvak Fiord, Morgan (op. cit. p.5) has identified a stock-like body of orthogneiss, a foliated rock of quartz monzonite to granodiorite composition.

Morgan also recognized the existence of several equivalent units west of the Ramah Group, where they have been reconstituted by the Hudsonian orogeny.

II. 3. Recent Development of Ideas.

Geochronological investigations in southwestern Greenland in the early 1970's revealed that the region contained the oldest rocks known on Earth -- metamorphic rocks which were probably vestiges of the early crust of the earth in existance three and one-half billion years ago, (Black, Gale, Moorbath, Pankhurst, and McGregor, 1971). Detailed mapping by V. R. McGregor between 1963 and 1970 culminated in the establishment of a long and complex history of intrusion, deposition and deformation for the early crustal segment around Godthabsfjord (McGregor, 1973).

More than 35 years ago, Kranck (1939a, 1939b) was impressed by the similarity between the gneisses of Labrador and Greenland, so much so that he commented that there was " a good correspondence as regards geological events during Pre-Cambrian time on both sides of the Labrador Sea." (Kranck, 1939b, p.80). More recently, Bridgwater, Escher, Jackson, Taylor and Windley (1973) similarly compared Greenland and Labrador using the structural provinces of Eastern Canada and their equivalents in the Precambrian block of Greenland. This eventually led to the definition of a North Atlantic Archean craton, encompassing the Nain Province in Labrador, the pre-Ketilidian in Greenland and the pre-Laxfordian of northern Scotland (Bridgwater, Watson and Windley, 1973). (Figure 5).

One of the implications of the definition of an old cratonic nucleus to the continental regions of the North Atlantic was that if the Nain province of Labrador was equivalent to the Archean block of Greenland, then very early crustal rocks might also be preserved in northern Labrador. This was confirmed by Hurst (1974) with a zircon U-Pb age of circa 3400 million years for metamorphic rocks which underlie the Mugford Group at Lost Channel, 150 km North of Nain.

Detailed investigation of a small area of the gneisses at Saglek Fiord during the summer of 1974 (Bridgwater, Collerson, Hurst and Jesseau, 1975) revealed that the geological evolution of this part of the Nain Province in

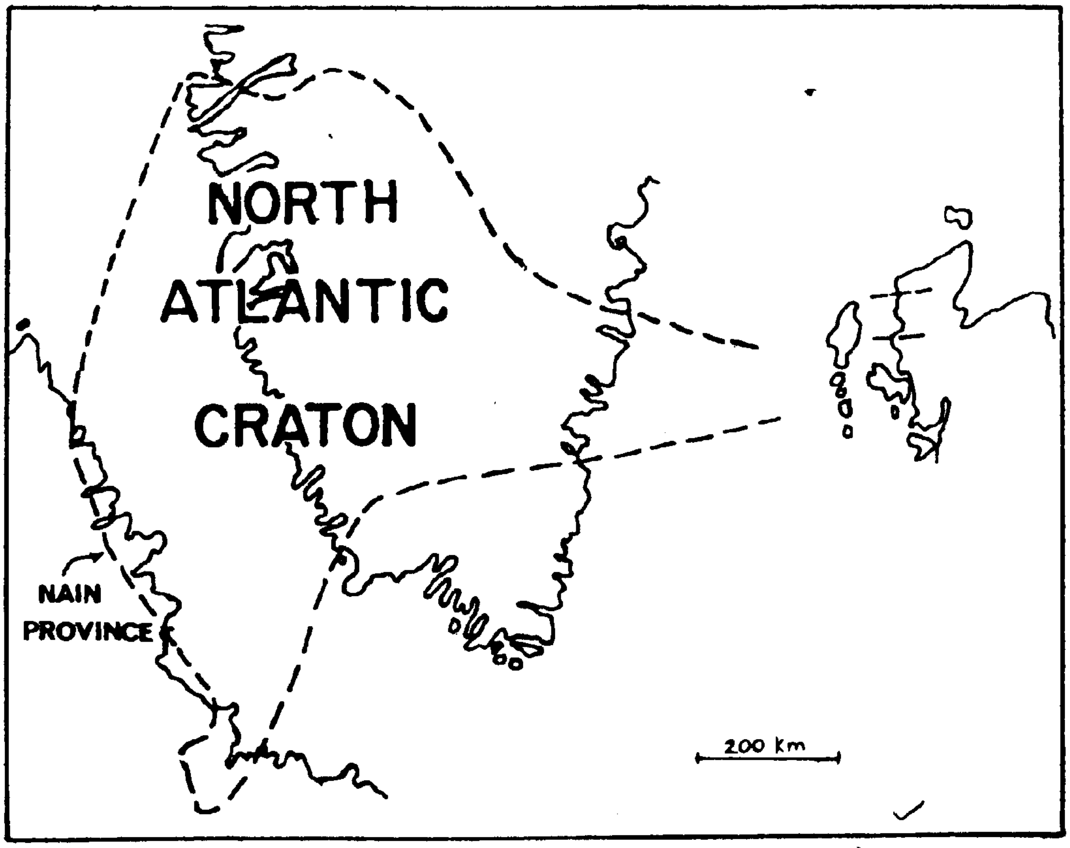

Figure 5. The distribution of Archean rocks within eastern Labrador, central Greenland and northern Scotland which define the North Atlantic craton (from Bridgwater et al., 1973 b).

TABLE I

Main geological events in the Saglek area and comparison with the Godthaabsfjord area of West Greenland

Labrador (Saglek Bay)	Age (m.y.)	West Greenland	Age (m.y.)
Metamorphism and deformation of Proterozoic cover (increasing to granulite facies in the west across the Archaean/Churchill boundary). Considerable thrusting	1300–2000	Proterozoic deformation and high-grade metamorphism to the north and south of the Archaean block	1600 - 2400
Deposition of Proterozoic cover rocks		Deposition of Proterozoic cover (Ketilidian)	
Injection of basic dyke swarms	2300 ± 300	Injection of basic dykes swarms	2300 ± 300
Widespread injection of late to post tectonic granites in shear zones. Retrogression of Archaean granulite facies. Faulting with area to west of Handy Fault possibly thrust upwards with respect to eastern area	>2400 <3100	Injection of late to post tectonic granites Widespread retrogression of regional granulite facies gneisses accompanied by considerable migmatization	2500–2700
High-grade metamorphism reaching granulite facies in west of Archaean block. Considerable anatexis	>2400 <3100	High-grade metamorphism reaching granulite facies over large areas of the craton. Considerable anatexis under high-grade conditions	2700-2900
Major period(s) of folding		Major folding producing interference patterns	
Considerable remobilization of earlier gneisses, injection of granitic veins (the undifferentiated gneisses)	ca. 3100	Injection of Nuk calc-alkaline suite Godthaabsfjord	3040
		Possible remobilization of earlier gneisses	
Intercalation (probably by thrusting) of supracrustal material with older (Uivak) gneisses		Intercalation of supracrustal rocks, anorthosites and earlier gneisses by thrusting	
*Emplacement of calcic anorthosites in gneisses south of Saglek		Emplacement of calcic anorthosite suite	
**Deposition of supracrustal sequences including basic and ultrabasic igneous rocks, layered feldspathic igneous bodies, impure quartzites, pelites and minor marbles		Deposition of Malene supracrustal suite** and equivalents (basic and ultrabasic lavas and sills, pelites, aluminous quartzites some intermediate volcanics)	
Injection of Saglek dykes (tholeiites)		Injection of Ameralik dykes	
Deformation and metamorphism		Deformation of Amitsoq gneisses accompanied by high-grade metamorphism and possibly regional homogonization	
Intrusion of iron-rich suite of Uivak gneisses. Deformation and formation of majority of pegmatitic layers in the early grey gneisses. Possible regional metasomatism. Intrusion of grey gneisses	3600–3700	Intrusion of Amitsoq gneisses (calc-alkaline suite plus iron-rich suite)	3600–3800
Deposition of very early supracrustal		Deposition and deformation of the	

Labrador closely paralleled that of the Godthabsfjord region of west Greenland (Table 1).

The evolutionary model for the Saglek area may be summarized as follows (Bridgwater et al, 1975; Collerson, Jesseau and Bridgwater, 1976; Hurst, Bridgwater, Collerson and Wetherill, 1975). The oldest recognized lithology of areal extent consists dominantly of foliated tonalitic to granodioritic rocks (the Uivak gneisses), locally rich in pre-Uivak inclusions. These gneisses include at least two chemically distinctive igneous intrusive suites, demonstrably separated in time, but both cut by a swarm of porphyritic diabase dykes, now amphibolites (the Saglek dykes). [It is curious to note that even though field relationships indicate the Uivak gneisses have been clearly derived from more than one intrusive series, and the Uivak I portion was metamorphosed and complexly deformed prior to the injection of Uivak II, the suite as a whole gives a whole-rock Rb-Sr age of 3622 ± 72 million years with both Uivak I and II falling on the same well-defined isochron. Hurst et al. (1975) have interpreted this feature to be a result of isotopic homogenization during metamorphism, rather than a primary igneous age. More recently Bridgwater and Collerson (1976) have advocated a major period of K and Rb metasomatism at 3.622 m.y to explain the homogenization of the two suites.] Although the Saglek dykes occur largely as disrupted pods rotated into parallelism with the Uivak foliation, undisputed discordant relationships can be rarely observed. Tectonically interleaved with the Uivak gneisses are a series of metasediments, amphibolites, layered meta-igneous basic intrusions and ultramafic rocks known collectively as the Upernavik supracrustals. No Saglek dykes have yet been recognized within the supracrustal series. Younger quartzofeldspathic gneisses derived by remobilization of the Uivak gneisses ~3133 ± 156 million years ago occur as foliated sheets within the earlier gneisses and supracrustals. Lensoid, white-grey granite masses possessing a simple anastomosing fabric are believed to have been emplaced late in the 3.1 b.y event. Later events in the area include emplacement of granites in shear belts transgressing all earlier structures, intrusion of post-tectonic diabase dykes, and movement on the Handy Fault.

During reconnaissance geochronological sampling of the Labrador coast in the summer of 1973, Barton (1974) collected a suite of rock from Hebron Fiord, from which he has recently reported a whole-rock Rb-Sr age of 3618 ± 106 million years (Barton, 1975). This age is equivalent to that of the Uivak gneisses, and indeed, the rocks sampled by Barton have been shown to be part of the Uivak suite (Collerson, Ryan and Bridgwater, in prep.), even though at Hebron the Uivak gneisses occupy restricted enclaves in dominantly remobilized and refoliated quartzofeldspathic gneisses.

The work carried out in the Saglek region during the past field season (Collerson, Bridgwater and Vocke, in prep.) has included extending the mapping to the east and west along the fiord, a study of the structural evolution of the gneisses west of the Handy Fault, and refining the established relationships. Newly discovered areas of low intensity deformation within the Uivak gneisses offer possibilities of "seeing back" to the very early structural evolution of the region.

II.4. Purpose of Present Study, Field Techniques and Weather Limitations on Project.

The present study was carried out in an area approximately 50 km south of Saglek, over a period of 17 days between July 20 and August 22, 1975. The mapping has revealed that the rocks of this region are dominantly the "undifferentiated gneisses" of Bridgwater <u>et al</u>., (1975) (herein termed the Iterungnek gneisses), ie. those foliated rocks which have been derived by remobilization of the Uivak suite ca. 3100 million years ago. Although small areas of the earlier Uivak gneisses have been identified, they all exhibit effects of intense deformation which has rotated discordant Saglek dykes into conformity with the Uivak foliation and disrupted them to form boudinaged horizons. The presence of a well exposed region exhibiting the superposition of another period of deformation and "gneissification" upon the Uivak migmatites has provided an opportunity to study deformation patterns and processes of refoliation in Early Archean gneisses.

Mapping of the thesis-area was carried out by overland traverses, plotting data on acetate overlays of vertical air photographs on a scale of 1 inch to 0.25 miles (1 cm = 0.16 km). Access to regions directly adjacent to Iterungnek and Hebron fiords was greatly facilitated by the use of a 14 ft. ($\sim$5 m) inflatable, heavyduty rubber boat. Lithologies were differentiated on a gross scale, and structural data recorded at each station during approximately two weeks of hit-and-run mapping. It was the intention to follow up the lithological distinction with detailed structural mapping by tracing-out individual marker units and recording as much structural data as possible to enable a plausible structural picture to emerge. Unfortunately, the weather during the field season was far from co-operative, with fog, rain and high winds for the greater part of the summer. As a result, many of the objectives of the study were not accomplished to such an extent that they can be used conclusively in accessing the structural evolution of the area. Regions for which the writer has little information, except of a reconnaissance nature, include the supracrustal gneiss relationship on the North side of Hebron

Fiord at the western margin of the map-area, and a large block of gneisses in the central part of the area on the South side of Iterungnek fiord. Traverses in these two areas indicate probable fold closures, which are indicated on the accompanying geological map (in back pocket) for Hebron, but data are too scanty to define these on Iterungnek fiord. More detailed mapping is required to delineate geological patterns in these areas.

CHAPTER III

LITHOLOGY AND PETROLOGY

III.1. Nomenclature.

The lithological subdivisions of the Archean gneisses between Iterungnek Fiord and Hebron Fiord correspond to those of the Saglek area (terminology following Bridgwater et al, 1975; Collerson, Jesseau and Bridgwater, 1976a) namely, Uivak gneisses containing pre-Uivak inclusions and Saglek dykes, the reworked equivalents of these early gneisses with associated syntectonic granitic sheets, and elongate basic gneiss and/or metasedimentary belts probably equivalent to the Upernavik supracrustal series. Other rocks within the study-area include ultramafic lens, several ages of pegmatites, and post-tectonic undeformed diabase dykes of (late Archean?-) early Proterozoic age. The southerly extension of the Handy Fault, defined by a broad valley with outcrops of pseudo-tachylite-veined mylonite, forms the western boundary of the map-area. Only one day of reconnaissance mapping was spent on the rocks west of this fault, and therefore they will not be considered in this account.

This section of the thesis describes the field appearance and petrology of the major rock units in the study area. The rock-units treated in detail below are (i) the Uivak gneisses (ii) the Upernavik metasediments and basic gneisses, and (iii) the Iterungnek gneisses, a younger series of tectonites formed partly through remobilization of the Uivak suite. Although the field characteristics of several other rock-types (eg. ultramafics, pre-Uivak inclusions) are described, and specific localities cited, a detailed petrographic treatment is beyond the scope of this thesis.

III.2 The Uivak Gneisses

This lithology, the oldest group of quartzofeldspathic rocks so far identified on the Labrador coast (3.6 billion years, Hurst et al., 1975), and widely distributed at Saglek, has not been identified as being of great extent in the area covered by this study. The Uivak gneisses are most easily recognized in clean, ice-scoured, coastal exposures where they appear as grey, biotite-rich foliated rocks of limited extent, usually enclosed by a pink to brown-yellow weathering K-feldspar (microcline)-rich gneiss which can be demonstrated at several localities to be formed by the remobilization and localized partial melting of the Uivak suite. Inland, in the lichen covered outcrops, it is usually impossible to distinguish subtle changes in lithology as on the coast, and areas of Uivak gneisses are not easily delineated.

The early gneisses are all intensely deformed as is demonstrated by their strongly foliated and banded appearance. The best exposures of Uivak gneisses in the map area are found in coastal stretches on the south shore of Iterungnek Fiord, in a small cove on the western arm of Jerusalem Harbour, and in the cove on the west side of Cape Nuvotannak.

The Uivak gneisses vary from massive light to dark-grey weathering, biotite foliated fine- to medium-grained rocks with minute whisps of quartz ± feldspar(s) concordant veining, to banded migmatites consisting of grey, biotite-rich layers from 2-50 cm wide intercalated with a medium to coarse-grained quartz-plagioclase-microcline fraction of similar thickness. The granitic pegmatoid parts frequently display a pinch and swell aspect, and the grey component often exhibits a streaky laminated appearance (Plate 1). Locally these white stripes may be seen to be derived from the extreme attenuation of feldspars [phenocrysts of the porphyritic Uivak II adamellite phase of Collerson et al., (1976)] or by the intense flattening and stretching of quartz-feldspar clots derived from the disruption of rootless intrafolial folds. These may have originated as synkinematic cross-cutting veins which (ptygmatically?) folded, later undergoing dismemberment and extension in response to the changing strain components. A possible evolutionary sequence is shown

PLATE 1

UIVAK GREY GNEISSES

1a. Typical grey, migmatitic Uivak gneisses on south shore of Iterungnek Fiord.

1b. Same as above. Note disrupted veins in melanocratic portion.

in Figure 6.

The alignment of biotite and the streaky character of the grey gneiss defines the dominant foliation, which at many localities has been overprinted by a new growth of biotite. The second foliation crosses the primary schistosity/ gneissosity at a very low angle, and only when this discordance is on the order of 15-25° is it easily detected. In such areas it is also possible to detect rotation of lozenge-shaped quartz-feldspar clots occasionally present in the gneisses, into the plane of the superposed foliation.

In certain areas (eg. on the west side of Morhardt Point, 58°16'N; 62°40'N[1]) the grey gneiss occurs as rotated, randomly oriented blocks with dimensions of a meter or more, brecciated and extensively net-veined by a system of granitic pegmatites believed to be due to the remobilization of the Uivak gneisses. These pegmatites are foliated parallel to their margins, and commonly follow trends mimicking the axial traces of folds in the gneiss (Plate 2a). In such exposures the Uivak layering is complexly folded and a new biotite foliation is developed, parallel to the axial planes of such folds (Plate 2b). In other areas (eg. west side of Jerusalem Harbour, 58°14'N; 62°37'40"W) the superimposed foliation is

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[1] Latitude and longitude determined from National Topographic System map-sheet 14L, Editión 1 MCE, Series A 501 (Hebron).

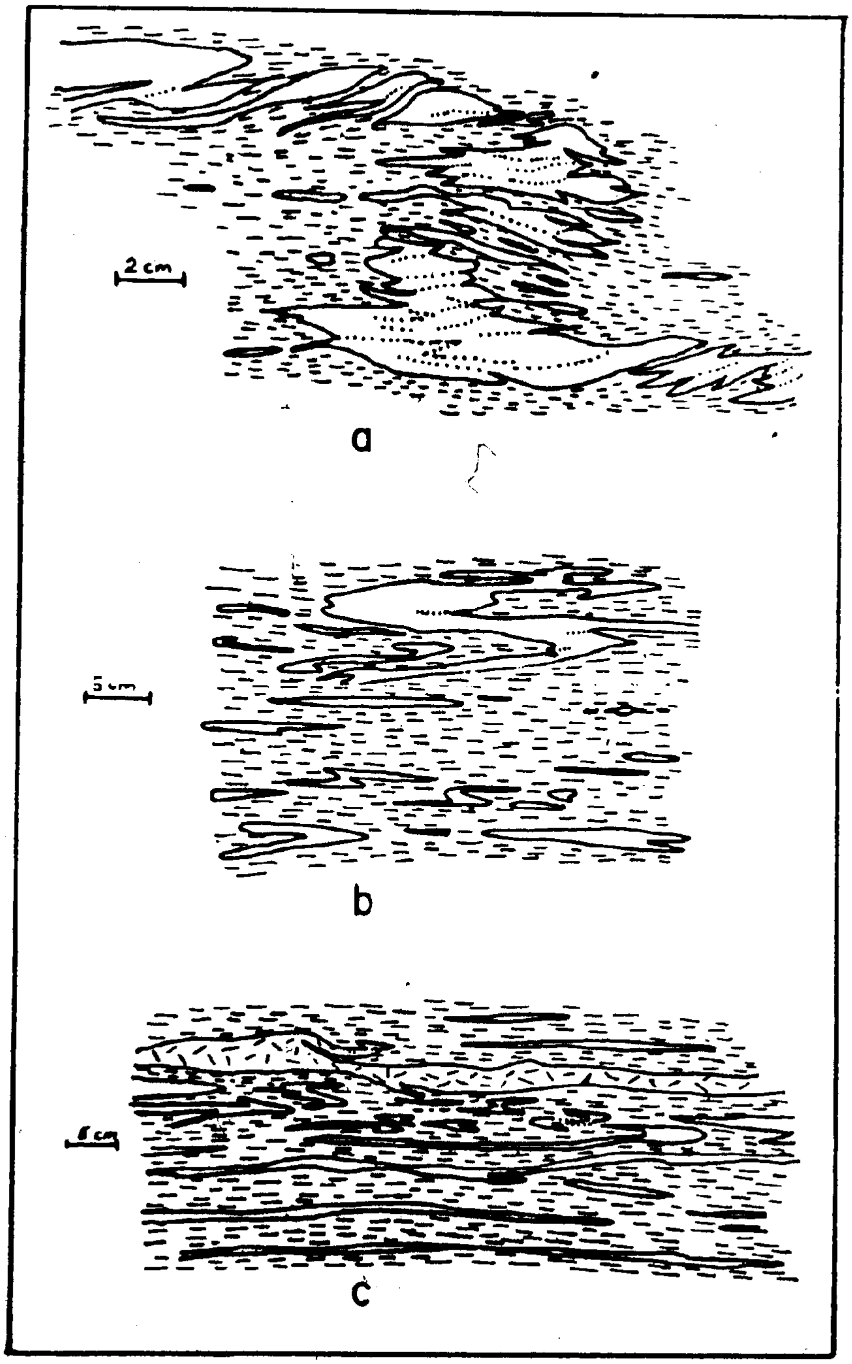

Figure 6. Schematic diagram to show disruption and attenuation of quartz-feldspar veins in Uivak gneiss. Cross-hatched pattern in (c) represents a later concordant pegmatite.

PLATE 2

PARTIALLY REMOBILIZED UIVAK GNEISSES

2a. Uivak gneisses on Morhardt Point. Note how pegmatites mimic the axial planes of folds of the gneissosity.

2b. Small-fold from gneisses above, showing axial planar fabric parallel to pencil.

defined by a series of dark-green elongate "blebs" of amphibole, replacing earlier pyroxene.

As a result of the highly strained nature of the Uivak gneisses in the map-area, it is very difficult to determine whether the rocks belong to the Uivak I or Uivak II suite described by Collerson et al., (1976a) and Bridgwater and Collerson (1976). There are a few areas where it appears that relic phenocrysts similar to those of the Uivak II adamellite are preserved, and in other regions (eg. Hebron Village; Jerusalem Harbour, 58°14'40"N; 62°38'10"W) dark-green to black monzonitic, ferro-dioritic and hornblenditic rocks occur within the grey gneisses. At Jerusalem Harbour a ferro-dioritic rock of this type appears to have been a narrow sheet intrusive into the grey gneisses enclosing it. These mafic portions of the Uivak gneisses have characteristics of the more iron-rich members of the Uivak II suite as described by Bridgwater and Collerson (1976, p.52). Most commonly however, the Uivak gneisses are nondescript, migmatitic, light-grey, tonalitic rocks whose primary origin, whether Uivak I or Uivak II, cannot be ascertained (cf. Collerson et al., 1976a). Grey gneisses of this type are typical of vast expanses of the Precambrian continental crust (cf. Tarney, Skinner and Sheraton, 1972; Marmo, 1971; Wynne-Edwards and Hasan, 1972; Viljoen and Viljoen, 1970;

Glikson and Sheraton, 1972; Hunter, 1974).

The foliated, homogeneous-looking, grey portions of the Uivak gneisses studied display the following mineral assemblages:

Quartz-plagioclase-biotite

Quartz-plagioclase-biotite-microcline

Quartz-plagioclase-biotite-hornblende

Quartz-plagioclase-biotite-hornblende-microcline.

The more mafic members, probably of the iron-rich Uivak II suite (cf. Bridgwater and Collerson, 1976) contain

Quartz-plagioclase-biotite-clinopyroxene

Quartz-plagioclase-biotite-clinopyroxene-hornblende.

Accessory phases in the Uivak gneisses are invariably apatite, zircon and allanite. Granular epidote is sometimes present as a late-stage alteration product, especially affecting plagioclase, and monazite was observed in one thin section.

The microstructure[1] of the gneisses is generally a granoblastic[2] mosaic of interlocking inequigranular grains (Plate 3). This is more pronounced in thin sections cut normal to the mineral lineation (N-section) than those parallel to this lineation (P-section). The mineral fabric

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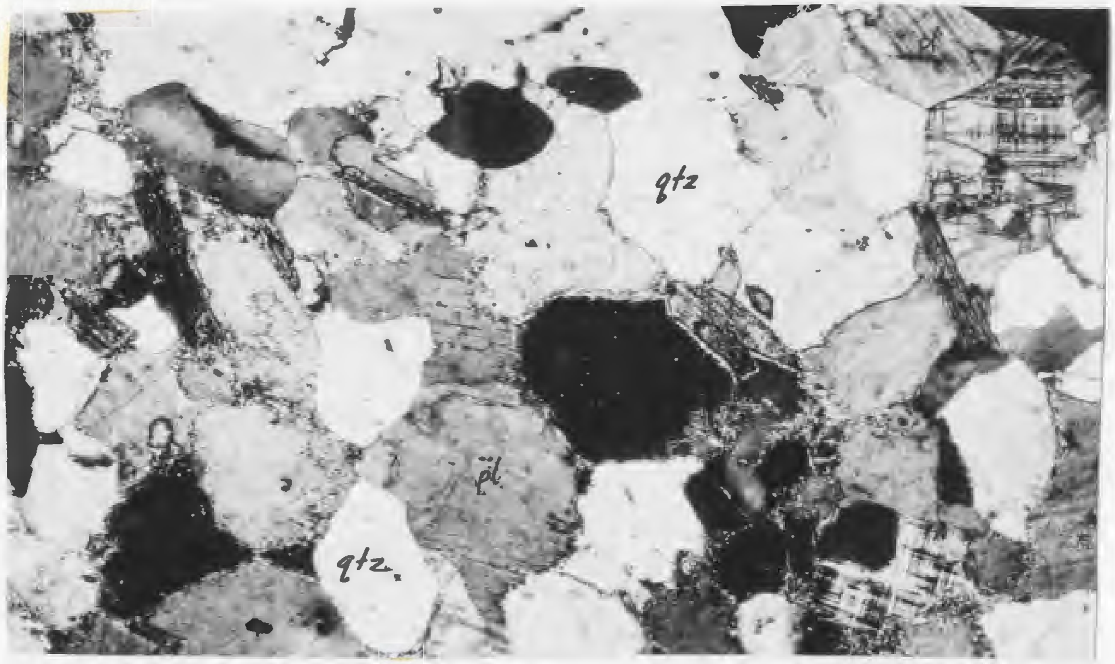
[1] "Microstructure" is used to describe the spatial distribution of the mineral grains in these rocks. "Texture", in metallurgical terminology means preferred orientation (see Vernon, 1968).

[2] Microstructural terminology follows the system of Collerson (1974)

PLATE 3

MICROSTRUCTURE OF UIVAK GNEISSES



3a. Granoblastic inequigranular texture in section normal to the lineation. (X 15)

3b. Foliation in section parallel to the mineral streaking lineation, which in this case is defined by elongate quartz. (X 15) (cf. Watterson, 1968, p.38) in thin section is defined by an alignment of biotite flakes and lenticular grains of quartz.

The actual amounts of each mineral in the gneisses is variable, especially the proportion of plagioclase to alkali feldspar. The mineralogy of the grey and pink Uivak I gneisses therefore gives rise to rocks which have igneous equivalents in tonalites, quartz diorites, granodiorites and quartz monzonites.[1] There is evidence from the petrological work that the wide variations noted may be attributable to additions of silica and potassium, therefore increasing the modal quartz and alkali feldspar. Thus the above compositions may not be indicative of such variations in the protoliths. The more mafic rocks studied, which are interpreted as being part of the iron-rich Uivak II suite have assemblages characteristic of ferro-diorites.

The Uivak gneisses described herein are both from areas which have escaped tectonic reconstitution, and also from enclaves in the Iterungnek gneisses where they have been only partially refoliated.

The general petrographic characteristics of the major minerals are described below. Since the region has undergone three periods of deformation of varying intensity subsequent to the formation of the Uivak gneisses (see

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[1] According to the IUGS Subcommission on the Systematics of Igneous Rocks (1973)

Ch.VI), some of the microstructural features observed in these rocks (eg. that of the quartz) may be late-stage developments. However where the relative ages of the microstructural patterns are known (eg. biotite reorientation) they are noted, especially those features which are present in Uivak gneisses from zones of re-foliation.

The quartz present in the Uivak gneisses shows two chief modes of occurrence, namely as small rounded pools < 0.2 mm in diameter surrounded by a more granoblastic aggregate of feldspar(s), or as ameboid, irregular equidimensional (up to 3 mm in diameter) and elongate grains (> 1 cm in length), the latter helping to define the foliation. In all cases it has undulose extinction (i.e. strain shadows); highly birefringent fluid inclusion trails are common. The larger grains display well-developed deformation bands. The boundaries of these bands, being zones of high strain, are loci for the generation of new grains within the larger grains (cf. Wilson, 1973). The recrystallization process of these new grains is "arrested", for their boundaries are commonly strongly sutured, instead of the straight 120° array expected for complete equilibrium following recovery (Smith, 1964, Vernon, 1968). The serrated boundaries also indicate grain boundary migration, i.e. an enlarging of the newly formed grains (Bell and Etheridge, 1973).

Deformation lamellae, at a high angle to the boundaries of the deformation bands (Plate 4a) have been observed in the quartz grains, especially in the Uivak gneisses from zones which are re-deformed (155c).[1]

In regions where the Uivak compositional layering is folded, and overprinted by the younger (Iterungnek) biotite foliation the quartz tends to recrystallize, or develop deformation bands and become elongate due to intra-crystalline slip, such that it forms an incipient foliation following the younger schistosity, even though the earlier banding is still conspicuous.

All microstructural features of the quartz in the Uivak gneisses can be thought of in terms of deformation largely by a dislocation mechanism. The deformation bands and lamellae, for example, indicate a slow strain rate (White, 1975a) or a creep type of deformation during which recovery has been an active process (cf. White 1975b; White and Treagus, 1975).

The quartz grains generally have curved, straight or scalloped grain boundaries against itself and the feldspars, but straight against the micas (see also Wilson, 1973; Vernon, 1968). However it has been observed to embay and corrode the feldspars, containing inclusions of them and the

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1 Numbers in parentheses refer to thin sections in the Memorial University Geology Department "Labrador Collection". All have the prefix BR-75-).

PLATE 4

MICROSTRUCTURES OF UIVAK GNEISSES

4a. Deformation lamellae in quartz. (X 120)

4b. Deformation lamellae parallel to kink boundary in plagioclase feldspar. (X 60) other mineral species present in the rock. These features are interpreted to indicate that there has been some introduction of quartz into these rocks following their initial crystallization or alternatively, there has been some remobilization of the quartz. The small pools between the other constituents may be interpreted in a similar manner.

Plagioclase commonly forms equidimensional grains with an average size of 1x1 mm, with the composition of oligoclase-andesine (An_{25-38}) in the felsic rocks and oligoclase (An_{28}) in the more iron-rich types. The degree of twinning - the most common of which is albite - varies. Many grains are untwinned, others have "faded" twinning, while others have been very sharp twin planes. If the criteria of Vance (1961) and Vernon (1965) are applied, then the forms of these twins indicate that the majority are produced by deformation.

The feldspar is very susceptible to alteration; sericite is profusely developed, especially along twin planes and grain boundaries, and granular epidote and carbonate are not uncommon. Many grains show strain effects - undulose extinction, the development of kink bands, and secondary (mechanical) glide twins. The lack of distinct, optically determinable fracturing on the kink band boundaries indicate they formed by plastic rather than brittle, processes (Borg and Heard, 1971; Vernon, 1975). In the kink bands primary lamellae are obliterated, and mechanical albite twins parallel to the kink boundaries are developed (Plate 4b). In other grains, single primary lamellae become narrow multiples within the kink band, and then continue on the other side of the kink with the same initial dimension.

The grain boundaries with other species vary from straight or slightly curved to embayed, the latter especially against quartz and microcline. The plagioclase/microcline interfaces are also sites of bulbous myrmekite growth, the "worms" of quartz penetrating the plagioclase (see below). Also when plagioclase is in contact with microcline, the former may show a narrow halo ($\sim$0.1 mm wide) which is in slightly different optical orientation than the rest of the grain (23a). Inclusions of quartz and microcline in plagioclase are rounded, indicating a close approach to microstructural equilibrium between the feldspar and its inclusions (Vernon, 1968; Kretz, 1966).

Four varieties of biotite are recognizable in the thin sections of the Uivak gneisses studied, viz. that of the original Uivak foliation, the overprinting (Iterungnek) fabric, randomly oriented aggregates, and a very late "shredded" variety.

The biotite which forms the foliation in the Uivak gneisses is intensely pleochroic (X = straw yellow;

Y = Z = greenish brown, dark brown, greenish black), and is characterized by the presence of inclusions of crystallographically oriented needles of acicular rutile[1] (sagenite; Hatch, Wells, and Wells (1972)). The mica occurs as subidiomorphic and xenomorphic grains up to 4 mm in length, parallel to the compositional banding. (Plate 5a).

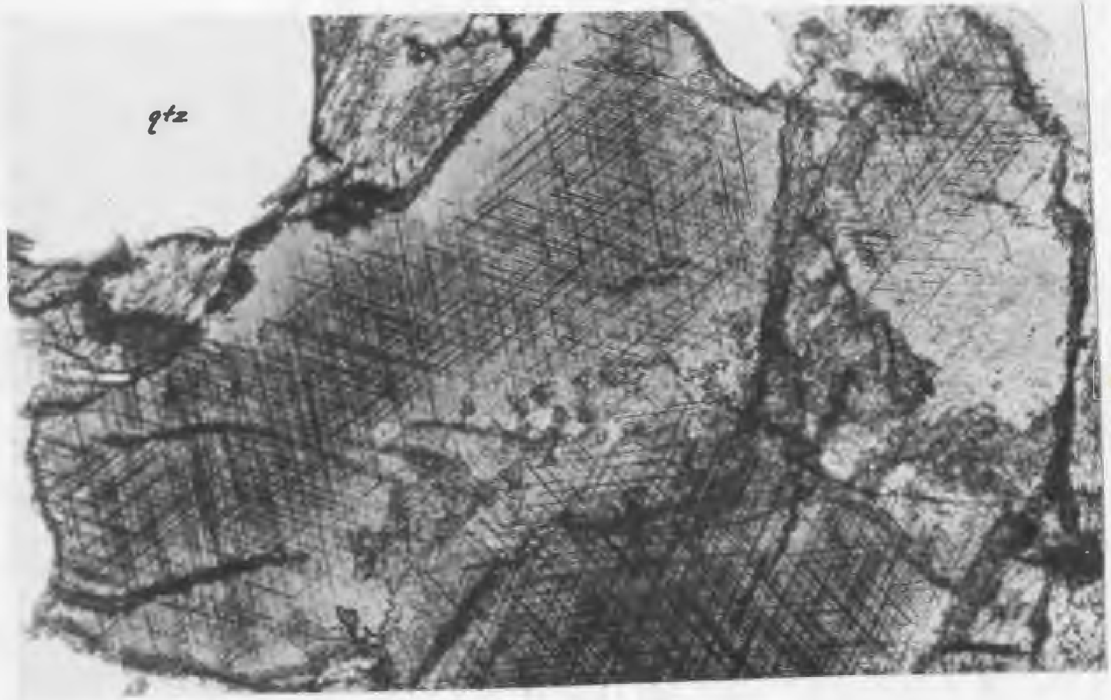
A second variety of biotite forms the axial planar foliation to folds of Uivak gneiss in the zones where the gneisses are reconstituted; it cross-cuts the Uivak compositional banding and its schistosity. It is similar in size to the earlier mica, but has a different pleochroism (X = buff, Y = Z = reddish brown), and generally lacks the rutile needles of the earlier biotite. The sagenitic biotite in the folded grey gneisses (125c) is largely reoriented parallel to the new mica foliation.

A third variety of biotite occurs as stellate aggregates up to 1 cm in diameter which displays a needle-like or skeletal appearance, and is larger than the fabric forming varieties. The pleochroism is X = pale yellow, Y = Z = blue green, grass green. It is devoid of inclusions, except zircon granules giving pleochroic haloes. This green mica occurs either associated with quartz and magnetite, apparently having no relation to the other minerals in the rock (31a),

[1] This cannot be used as a diagnostic feature of the Uivak gneisses however, since Collerson (pers. comm.) has found sagenitic biotite in late, foliated granitic sheets at Saglek.

PLATE 5

BIOTITE IN THE UIVAK GNEISSES



5a. Rutilized or sagenitic biotite characteristic of the Uivak gneisses. (X 60)

5b. Late stage "shredded" biotite. (X 100) or in association with a blue-green amphibole (125c) which is replaced by symplectites of quartz-green biotite (see below). The unoriented aspect of the green biotite suggests that it crystallized essentially under static conditions, i.e. is probably largely a thermal transformation of the amphibole.

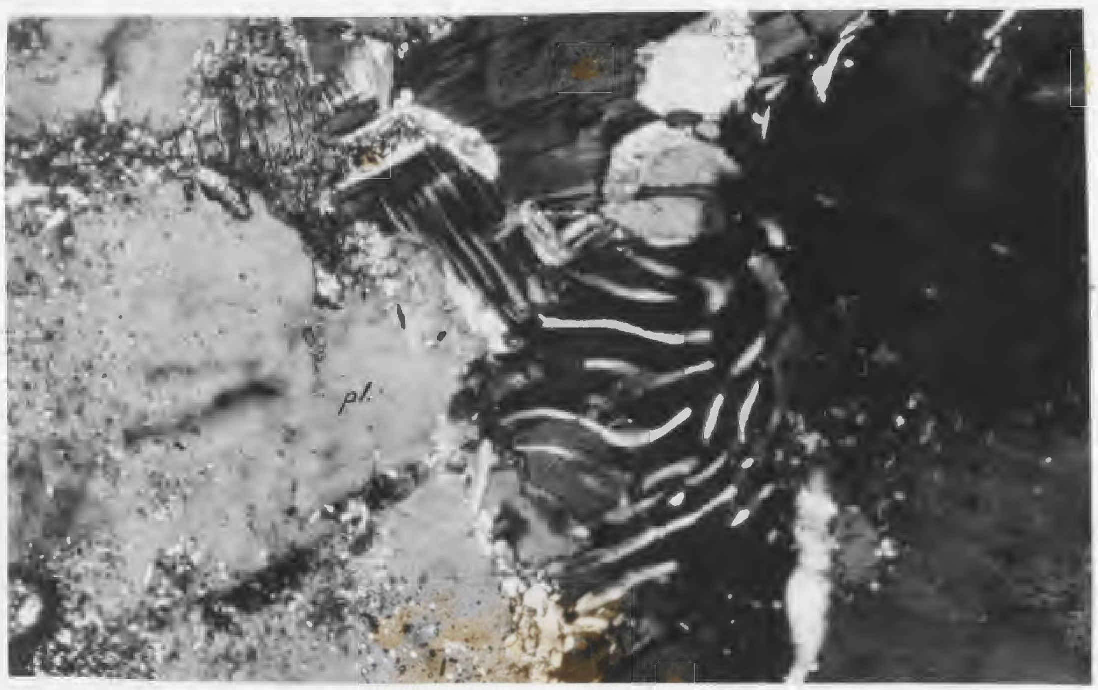
The fourth form of biotite is a green and brown "shredded" form, rarely in well-defined grains. It occurs as secondary overgrowths on the earlier micas, as coronas on opaques, and penetrates along mineral grain boundary and into fractures in feldspar and hornblende (Plate 5b). When this biotite does form discrete flakes, these usually nucleate perpendicular to the (001) of the earlier mica, but some do overgrow in the same crystallographic orientation. All occurrences of this mica indicate that it is a rather late-stage mineral in the rocks.

The only potassium feldspar detected in the Uivak gneisses is microcline. In contrast to the variably altered aspect of the plagioclase, microcline is fresh and unaltered. It has a xenomorphic form varying from minute grains to a maximum of 3x3 mm. The characteristic spindle-shaped cross-hatched twinning is ubiquitous, and a variety of perthitic forms (Plate 6a) have been observed in this feldspar e.g. ribbon, flame, patch, stringlet (see Spry, 1969, p.182).

PLATE 6

MICROCLINE IN THE UIVAK GNEISSES

6a. Perthitic microcline. (X 100)



6b. Myrmekite growth at a microcline-plagioclase interface. (X 60)

Grain boundaries with itself and other constituents of the rock vary from straight to embayed, the latter most common against plagioclase, accompanied by vermicular quartz penetrating the plagioclase (Plate 6b). A similar phenomenon is seen within plagioclase inclusions in the alkali feldspar. Myrmekite is not observed at all plagioclase/microcline interfaces, but its presence does indicate that at least some of the microcline probably formed at the expense of plagioclase, either by introduction of K_2O to the system (eg. Hunter, 1973) or else by exsolution caused by deformation (Phillips and Carr, 1973). However, other mechanisms may cause similar myrmekitic intergrowths (for a review, see Phillips, 1974).

A green amphibole is present in the Uivak II ferrodiorites, and to a lesser extent in the grey gneisses of the Uivak I suite. The hornblende is considered to be of two ages, namely (i) that present in the compositional bands in the Uivak gneisses and (ii) that in blotchy zones in the grey gneisses.

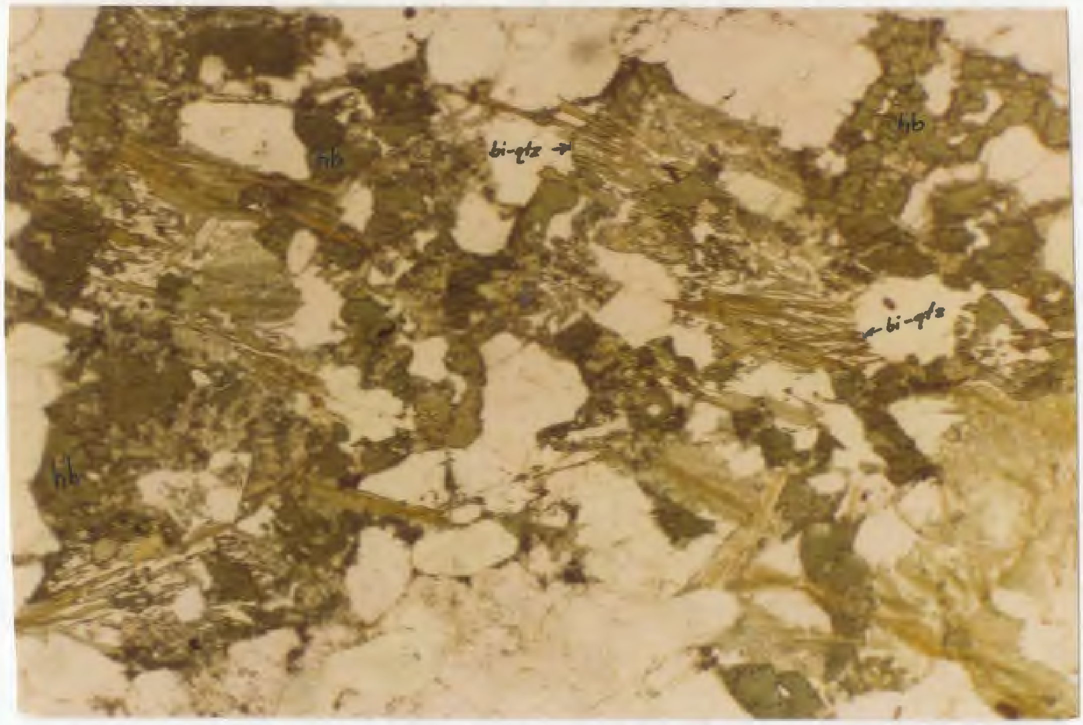
The amphibole in the ferrodiorites, and more rarely in the grey gneiss, has a maximum size of 3 x 2 mm, and has a xenomorphic to subidiomorphic form. Its pleochroism is pronounced (X = buff, Y = greenish brown, Z = grass-green), and optic angles determined (on the order of 40°) indicate a composition towards the ferrohastingsite end-member of the hornblende series (Deer, Howie and Zussman, 1971). In some examples this hornblende has been observed to overgrow sagenitic biotite, but more commonly the two co-exist as discrete phases. However, there are numerous examples in thin section where this amphibole has been overgrown by later clinopyroxene in which it remains as relics.

The second hornblende has been observed only in one thin section (125c), where it forms xenomorphic, porphyroblastic grains, often granular but in optical continuity, in plagioclase-quartz blotches found in small Uivak enclaves in the Iterungnek gneisses. These blotchy zones are relatively free of the brown Uivak biotite, suggesting that it may have been involved in the hornblende-producing reaction (Mehnert and Büsch, 1966, p.254). These blotchy zones, with the green hornblende blebs, are interpreted as areas where melting has been initiated within the older grey gneiss, under later high grade metamorphic conditions. (Büsch, Schneider and Mehnert, 1974; Wooden, Goldich and Ankenbauer, 1975). The hornblende of these irregular blotches is larger (up to 1 cm. in size) than that occurring in the compositional bands in the gneiss, and has the following pleochroic scheme: X = yellow, Y = blue-green and Z = green. It is commonly replaced by stellate green biotite-quartz symplectites as noted earlier (Plate 7a). Similar stellate arrays have been found replacing garnet in blebby granulite facies gneisses at Saglek (K. D. Collerson, pers. comm.). However, the PT conditions may not have been such that garnet would crystallize in the rocks under study here, and hornblende crystallized instead (cf. Büsch et al, 1974, p.366) which gave rise to similar biotite-quartz products on retrogression (see also Schneider, 1974).

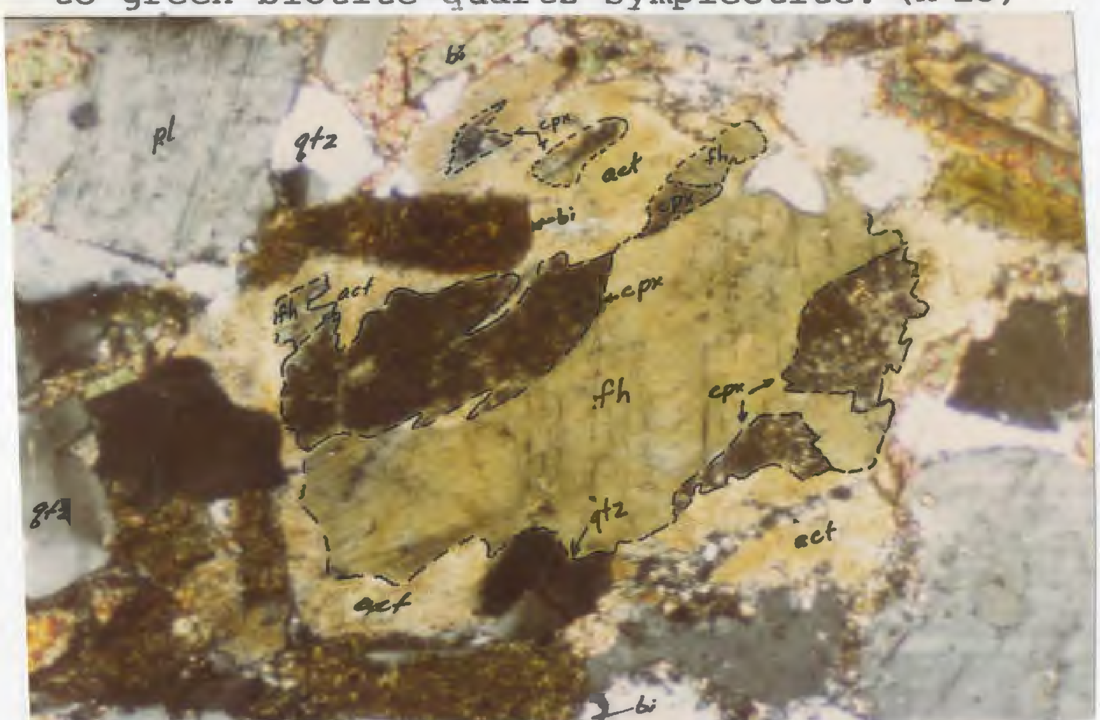
A pale-green weakly pleochroic clinopyroxene (hedenbergite) is present in the iron-rich dioritic gneisses. Overgrowths on hornblende, and the presence of hornblende inclusions indicate that it is a prograde dehydration transformation of the earlier ferrohastingsite. In areas of tight folding, the clinopyroxene forms an axial planar fabric, overgrowing the Uivak banding, and giving the rock a pronounced blebby aspect. It typically occurs as relic grains or "islands" surrounded by a massive-looking pale green actinolitic amphibole, although all stages of transformation have been observed, from slight marginal alteration to complete pseudomorphs. In some thin sections one can observe hornblende (ferrohastingsite) overgrown by clinopyroxene, surrounded by a corona of actinolite which penetrates fractures and cleavage traces of both (Plate 7b). The clinopyroxene to actinolite reaction appears to have occurred in a non-stressed environment, an indication that conditions of metamorphic recrystallization outlasted the

PLATE 7

HORNBLENDE AND CLINOPYROXENE IN THE UIVAK GNEISSES



7a. Blue-green hornblende in blotchy zone from partially remobilized Uivak gneiss breaking down to green biotite-quartz symplectite. (X 15)



7b. Progressive transformation: ferrohastingsite → clinopyroxene (hedenbigite?) → actinolite in ferrodiorite. (X 60) deformation.

Another variety of secondary amphibole is also present in the clinopyroxene-bearing rocks. It is colourless, has a bladed form in contrast to the massive actinolite, has parallel or nearly parallel extinction (very low $Z \wedge C$), and never retains any relics of what it has replaced. It is possible that this bladed amphibole is pseudomorphing original orthopyroxene, none of which remains. This however, requires further petrographic investigation.

III. 2.1. The Saglek Dykes

The Uivak gneisses were identified and delineated in the field on the basis of numerous inclusions of porphyritic amphibolite, believed to be the remnants of a diabase dyke swarm intruded into the Uivak gneisses at sometime during their evolution, both rock types being subsequently deformed. The effect of such deformation has been to disrupt and rotate the Saglek dykes into parallelism with the resulting gneissosity. Alternatively the dykes may have been intruded parallel to the original gneissic layering. Rarely are intrusive relationships preserved. On the south shore of Iterungnek Fiord (58°14'30"N; 62°41'30"W) there occurs Uivak gneisses in which a few of the Saglek dykes show discordant contacts with, and small apophyses into, the surrounding

Uivak migmatites. However features such as these are uncommon; the dykes usually occur as dark-green to black coloured pods and lensoidal amphibolite bodies, from < 20 cm to > 5 m in length and < 5 cm to 1 m in width, forming linear inclusion trails parallel to the gneissosity in the country rocks.

During the field study the use of the name "Saglek dykes" was restricted to those amphibolite inclusions which displayed relic phenocrysts of plagioclase feldspar, or their deformed equivalents. The plagioclase usually occurs as well-preserved megacrysts (up to 5 cm in diameter) or aggregates of megacrysts in an equigranular, granoblastic, fine to medium-grained hornblende-feldspar matrix (Plate 8a). The weathering of the undeformed feldspar megacrysts in a few dykes gives the impression of original igneous zoning preserved. In areas of high finite strain the megacrysts are extremely elongate giving rise to a discontinuously banded amphibolite (Plate 8b).

Two thin sections of deformed Saglek dykes were studied. The chief minerals are hastingsitic hornblende, plagioclase, actinolite and quartz, with abundant accessory opaque oxides (magnetite), granular epidote and minor muscovite.

The hornblende has a xenomorphic to subidiomorphic form with a strong pleochroism (X = pale brown; Y = grass green, Z = brownish green). The plagioclase (An_{26}),

PLATE 8

SAGLEK DYKES

8a. Typical porphyritic character of Saglek dykes where least deformed.

8b. Deformed Saglek dyke. Feldspars are extremely attenuated and give rise to a streaky, banded amphibolite.

forming lenticular aggregates, is invariably twinned and deformed. Sericite and epidote alteration are widespread. A pale-green, weakly pleochroic actinolite, predominantly confined to the plagioclase-rich portions of the rock, is interpreted as replacing clinopyroxene. None of the clinopyroxene remains, but the habit of this amphibole is reminiscent of that observed in the mafic Uivak gneisses described earlier (p. 51). The actinolite is characterised by rims of granular and acicular epidote, most pronounced where the amphibole is in contact with plagioclase, and generally absent at contacts with the other phases. This relationship indicates that the epidote coronas are generated as a result of a reaction between plagioclase and actinolite. Minor greenish shredded biotite may occur with the epidote. The quartz in the Saglek dykes occurs as large, commonly elongate, grains (> 5 mm in length) throughout the rock, but predominates in the plagioclase-rich zones. Smaller ameboid quartz is also present, which encloses and/or embays other phases giving some (eg. hornblende) a resorbed appearance.

III. 2.2. Pre-Uivak Inclusions.

Also occurring within the early grey gneisses are numerous inclusions of metasediments, massive amphibolites and variably textured ultramafic rocks, all of which are considered to pre-date the igneous suites which were the precursors of the Uivak gneisses. These inclusions are generally several meters in dimension, although larger bodies may be present, as is described below. In areas where the Uivak gneisses have been remobilized, it is difficult to decide whether the inclusions are pre-Uivak or not, especially those found adjacent to the intercalated metasedimentary and amphibolite belts in the area. It can be demonstrated however, that many inclusions in such settings have been derived locally by a process of "stoping' from the supracrustal belts during remobilization of the surrounding gneisses. However several outcrops of Uivak gneiss with pre-Uivak inclusions have been recognized (Figure 7); two such inclusions are described below.

On the south shore of Iterungnek Fiord (58°14'15"N; 62°30'42"W) Uivak gneisses contain a lens of tightly folded, dense, foliated ultramafic rock, and several pods of cumulate-textured meta-melagabbro. The melagabbro texture consists of irregular, snowflake-like patches of plagioclase ± garnet in a hornblende-plagioclase matrix (Plate 9a). In another part of the same outcrop, this cumulate texture is deformed, folded and cross-cut by an undeformed Saglek dyke (Plate 9b). Such relationships demonstrate the activity of very early deformational/metamorphic and intrusive processes during the evolution of the gneiss complex, which in this case indicate a period of folding either after the

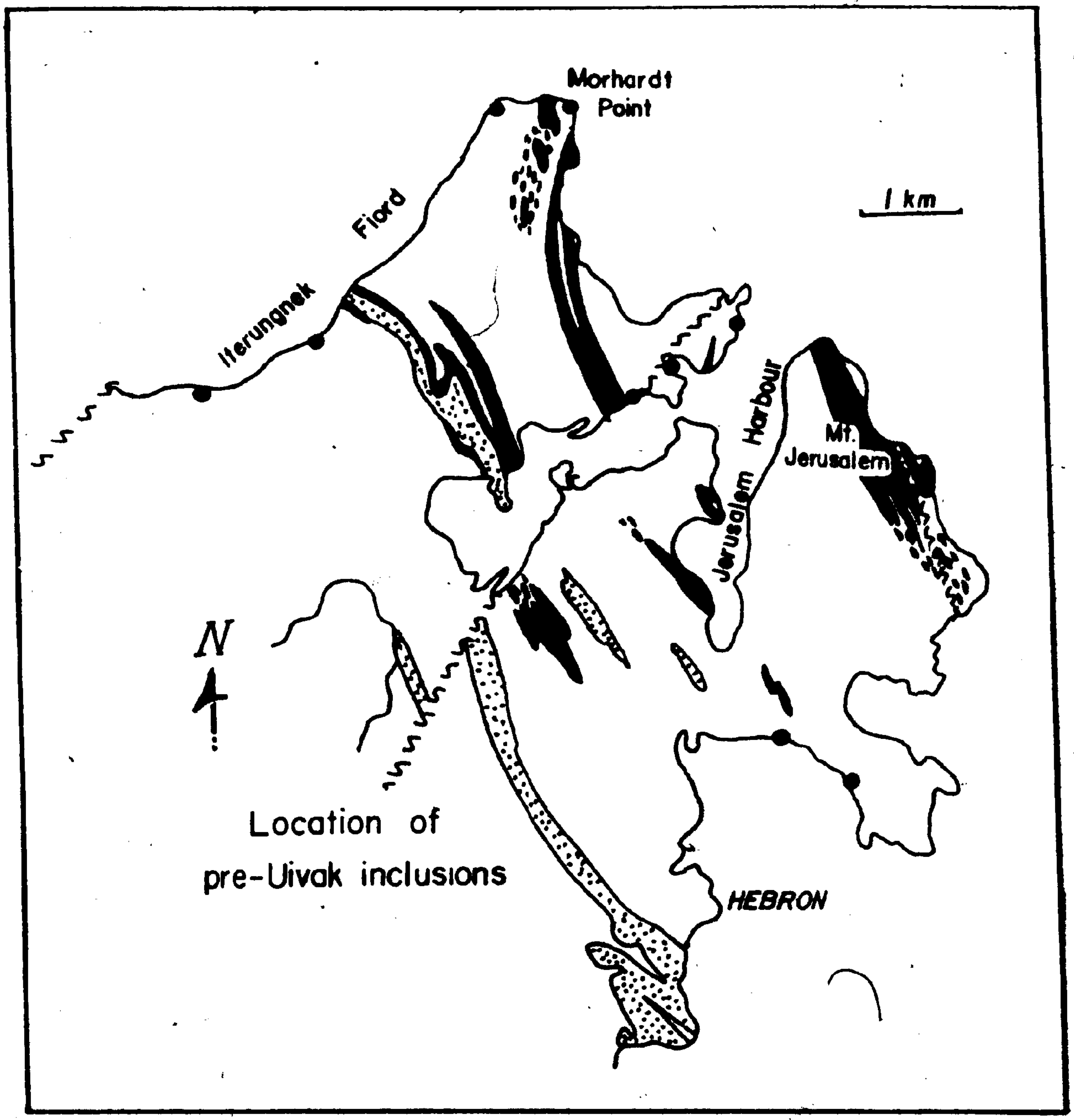


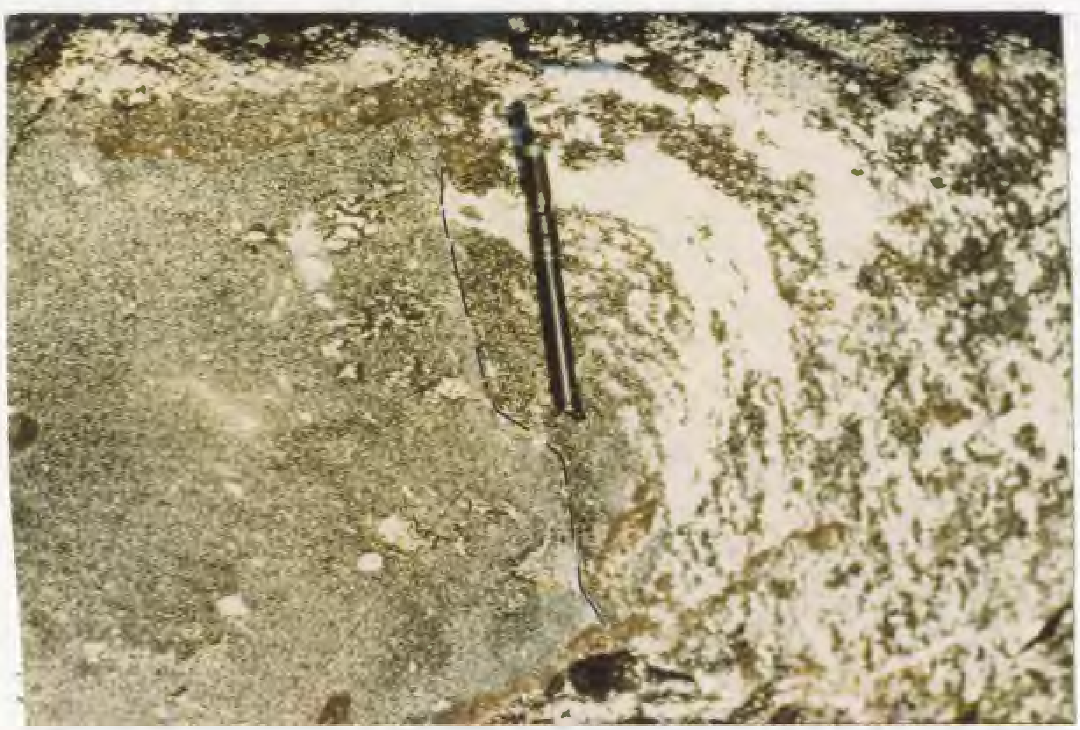
Figure 7. Sketch map showing locations of pre-Uivak inclusions in the map area.

Legend: solid black - basic gneiss
stippled - metasedimentary gneiss
unornamented - quartzofeldspathic gneisses (undifferentiated on map)
large solid dots - various pre-Uivak lithologies.

PLATE 9

PRE-UIVAK INCLUSION

9a. Snowflake-like cumulate texture in pre-Uivak meta-melagabbro, Iterungnek Fiord.



9b. Same outcrop. Cumulate texture has been flattened, folded and cut by porphyritic Saglek dyke (left).

inclusion was encorporated into the Uivak protolith or prior to its incorporation, but certainly pre-dating the intrusion of the dyke.

In reworked gneisses on the west side of the entrance to Jerusalem Harbour there are numerous mafic, ultramafic and metasedimentary inclusions which are interpreted as remnants of pre-Uivak lithologies. One such disrupted lens of pre-Uivak metasedimentary rock is ∿75 m in length and 1.5 m at its maximum width. It is in the form of one limb and part of the hinge zone of an isoclinally folded sequence, slightly discordant to the surrounding gneiss. The rocks of the inclusion include grey-brown granular impure quartzite, a pale green mafic rock (possibly a metabasic tuff), semipelite, and dense quartz-ironstones (quartz-amphibole-magnetite ± clinopyroxene ± garnet rocks). Inclusions,mineralogically similar to the latter found in the Amitsoq gneisses of Greenland are believed to be derived by intense silica contamination of banded ultramafic rocks (McGregor, 1973). However the association with metasediments here and elsewhere in the map-area (see below) suggest they may be sedimentary derivatives, for example metamorphosed iron-rich cherts. Also occurring within the above-mentioned inclusion is a concordant porphyritic amphibolite resembling a Saglek dyke.

Quartz-ironstones also occur as thin layers in a large metasedimentary inclusion (?) in the gneisses on the south side of the west arm of Jerusalem Harbour (58°14'25"N; 62°38'30"W). An isolated amphibolite showing a pronounced interfingering pattern with the gneisses, and marginally intruded by a foliated granite sheet is present approximately 500 m to the west. Such large isolated units in the gneisses may be pre-Uivak in age. However there is no unequivocal evidence to suggest that indeed they are pre-Uivak "mega-xenoliths" which have withstood the later reconsitution of the Uivak suite.

A detailed discussion of the petrology of these rocks is beyond the scope of this thesis. Only a few thin sections of these rocks have been examined, all exhibiting mineral assemblages diagnostic of the amphibolite facies. It should be noted however that similar inclusions in amphibolite facies gneisses at Saglek have assemblages which suggest an early period of granulite facies metamorphism, probably pre-Uivak in age (Collerson, et al., in prep.) Further descriptions of the various types of pre-Uivak inclusions from Saglek will be presented elsewhere by Collerson and Bridgwater, 1976).

III. 3. The Upernavik Supracrustals.

Intercalated with the Uivak gneisses at Saglek are a series of meta-sediments and layered amphibolites which Bridgwater et al (1975) termed the Upernavik supracrustals. The equivalent rocks in the present study area are discussed below under two headings, viz. (i) the metasedimentary belts, with associated (less abundant) basic gneiss and (ii) the layered basic gneiss belts, since both occur as individual map units in the area.

III. 3.1. The Metasedimentary Rocks.

Metasedimentary rocks, with associated bands of basic gneiss, form three sinuous belts in the map-area. These supracrustal rocks are easily identified by their rusty weathering character, attributable to the presence of abundant biotite and disseminated pyrite in the metasediments.

The paragneisses are predominantly semi-pelitic and pelitic composition, but minor dark-brown, graphite-bearing marbles, green, banded calc-silicate rocks, and grey, impure quartzites occur as lens or pods up to 15 × 5 m in size within the successions.

The pelitic and semi-pelitic rocks are characteristically light rusty-brown or grey in colour, and contain interbanded discontinuous, concordant units of white, saccharoidal, garnetiferous granite (Plate 10 a). The metasediments frequently display a streaky appearance due to overlapping, elongate, lensoid clots of quartz and feldspar within a more homogeneous, foliated biotite-rich host. The banding in the paragneiss varies from a few centimeters to more than 2 m in thickness, and forms units from 5-50 m thick, interlayered with basic gneisses of similar thickness. Garnets, pale pink

PLATE 10

UPERNAVIK SUPRACRUSTALS

10a. Grey and rusty-weathering semi-pelitic gneisses with intercalated white, sugary, garnetiferous. granite displaying a pinch and swell aspect.

10b. Amphibolite units interlayered.with the meta-sediments. Note thick unit in hillside at center of photo.

to dark-red in colour, and up to 20 cm in diameter, are ubiquitous in the metasediments and have an apparent increased concentration in zones near the contact with the granitic fraction. Pinitized cordierite occurs as disseminated blue blebs up to 2 cm in diameter, and also forms distinct cordierite-rich horizons; recognizable sillimanite needles are associated with biotite in many outcrops of pelitic compositions.

Basic gneiss units interlayered with the metasedimentary rocks are on the order of 5-50 m in thickness (Plate 10 b), and vary from massive isotropic bodies to well-banded fissile rocks. They are dominantly hornblende-plagioclase rocks, but garnet is locally present, and in places gives rise to garnet-hornblende rocks with traces of feldspar and biotite.

Although no primary structures are preserved in the basic gneisses associated with the metasediments they are interpreted to be derived from volcanic horizons (eg. basaltic flows, mafic tuffs) or early mafic intrusions in the sediments. Such an origin for the basic rocks at Saglek has already been postulated by Collerson et al., (1976), and similar occurrences in Greenland have been shown to be derived from extrusive volcanic rocks (cf. McGregor, 1973; Anderson and Friend, 1973). There is no field or petrographic evidence to indicate an origin of the basic gneisses from argillaceous or calcareous rocks (cf. Smithson, Eikkan and Houston, 1971; Naha and Ray, 1970;

Winter, 1970, 1974).

Only the petrology of the metasediments is presented below. The mineralogy of the basic gneisses in the metasediments is similar to that presented later (III.3.2) for the large basic gneiss belts.

There is very little variation in the mineralogical composition of the metasedimentary rocks studied. The semi-pelitic and pelitic members are strongly foliated, with mica and sillimanite having pronounced preferred orientation between more granoblastic aggregates of the other constituents. Mineral assemblages observed are

Biotite-quartz-plagioclase-garnet-cordierite

Biotite-sillimanite-quartz-plagioclase-garnet-cordierite microcline

Biotite-sillimanite-quartz-plagioclase-microcline-garnet

Zircon, chlorite, opaque oxides, and muscovite may be present in accessory amounts.

The psammitic members of the paragneisses contain

Quartz-plagioclase -biotite-garnet

chlorite, opaque oxides, carbonate and epidote are also present.

Several of the massive and banded calc-silicates were studied, having the assemblage

Calcite-diopside-zoisite-microcline-quartz

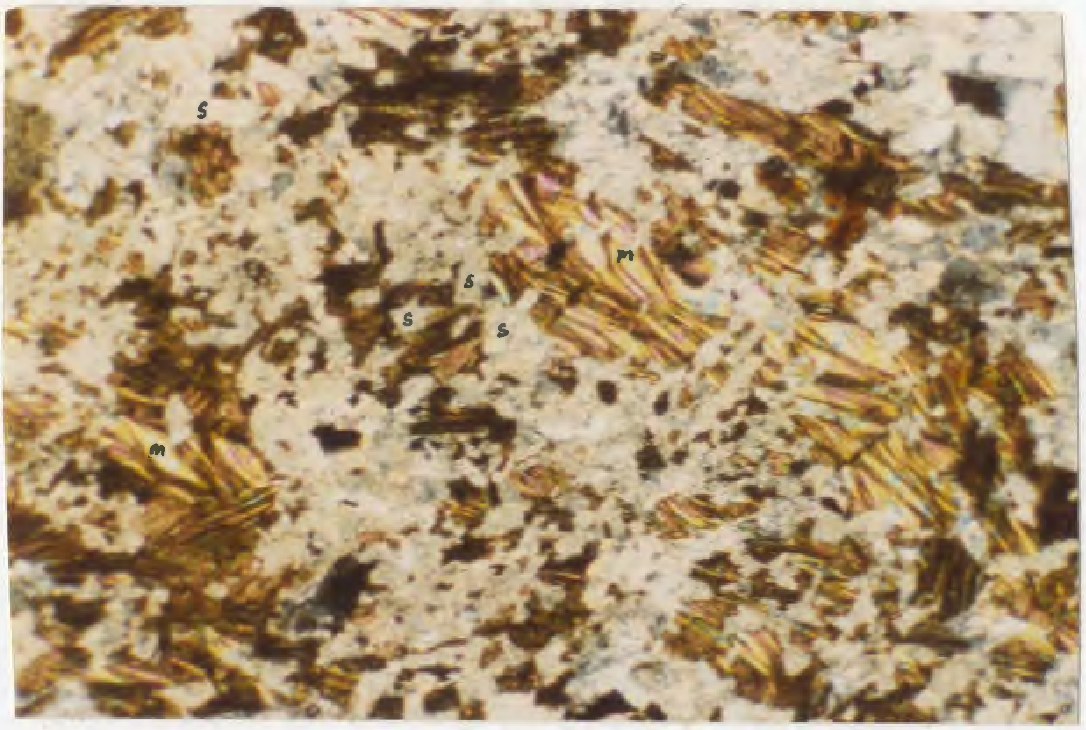
Sphene, pargasite, tremolite and pale green spinel are the chief accessory phases.

In the <u>pelitic</u> and <u>semi-pelitic</u> <u>gneisses</u> (semi-schists, in some cases), biotite is the chief ferromagnesian mineral. It occurs generally as subidiomorphic blades up to 4 × 1 mm, concentrated in specific bands in the rocks, thereby giving them a strongly foliated appearance. The biotite has very pronounced pleochroism from X = straw yellow, pale brown, colorless to Y = Z = foxy-red, orange-brown, dark rusty brown. Zircon inclusions with pleochroic haloes are commonly present, and there is minor retrogression to a pale green or colourless chlorite.

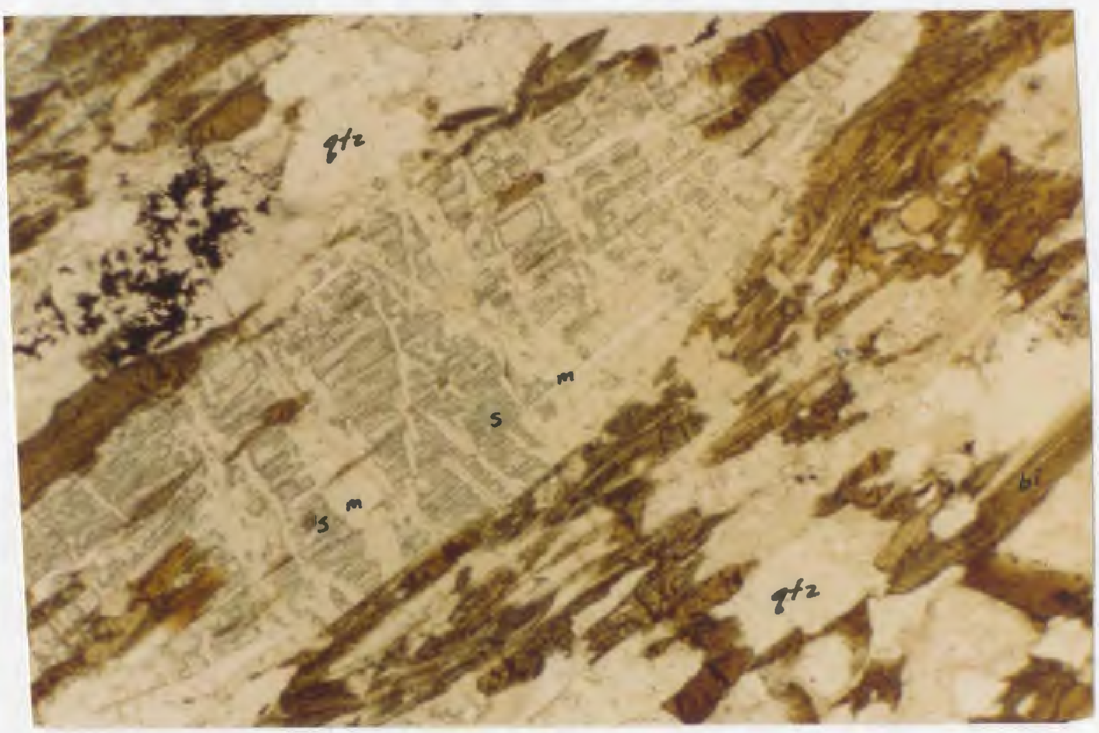
One rusty pelitic rock from Hebron (48b) displayed a very unusual relationship between biotite and muscovite. In N-section the biotite occurs as somewhat stubby crystal forms in a groundmass composed of very fine muscovite/sericite (most of which pseudomorphs original sillimanite) and fractured irregular quartz. Discrete flakes of muscovite are best developed when it replaces the elongate sillimanite needles or the diamond-shaped basal sections; radial growths occur on pyrite. The muscovite/sericite also replaces biotite, growing parallel to the cleavage traces, and "forceably expanding" the brown mica, such that individual mica grains become alternating intimate parallel growths of biotite and muscovite (Plate 11a). In sections parallel to the sillimanite lineation however, sillimanite is abundant, even though there

PLATE 11

MICROSTRUCTURE OF METASEDIMENTS



11a. Upernavik metasediment from Hebron. Section normal to lineation showing biotite-muscovite intergrowth, and "muscovitized" basal sections of sillimanite. (X 15)



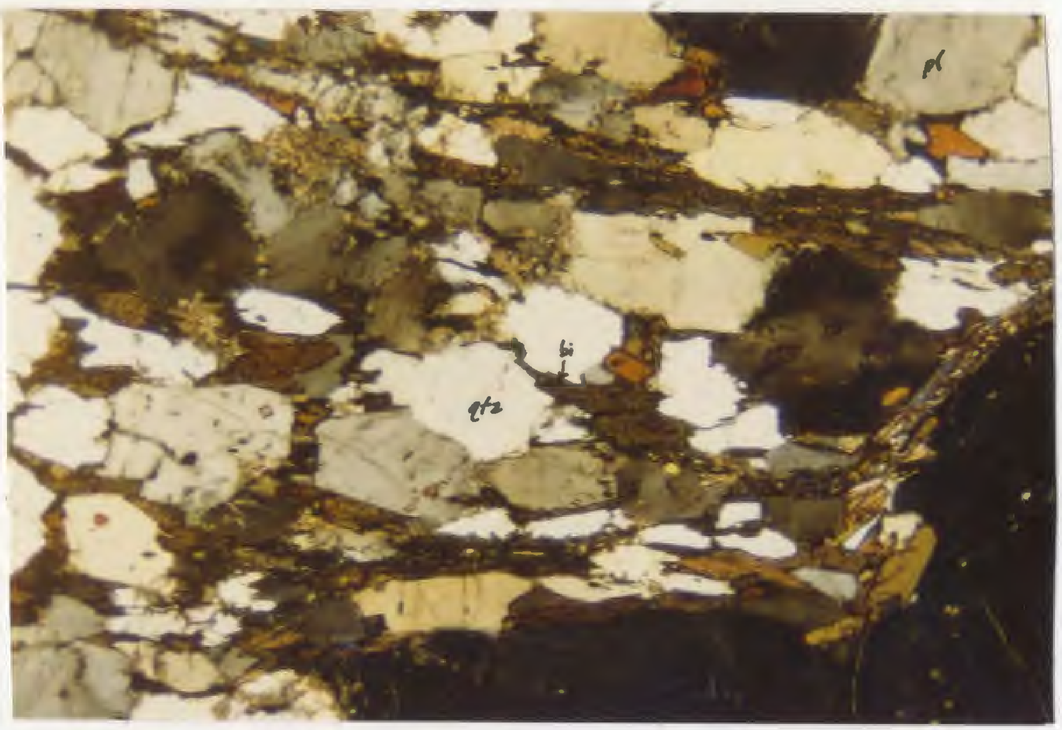
11b. Sillimanite aggregate partially replaced by muscovite (low relief). Plain light. (X 60) has been considerable replacement by muscovite, and the biotite rarely shows the intergrowth of muscovite observed in the other orientation.

Elongate sillimanite (up to 5 × 1 mm) also defines the foliation, and forms a lineation in the metasediments. The sillimanite occurs as needles, and aggregates of diamond shaped basal sections (normal to the lineation), associated with biotite, and commonly in pinite which has pseudomorphed cordierite. In some rocks sillimanite aggregates have been partially replaced by muscovite, as mentioned above (Plate 11b). Inclusions of the aluminosilicate in plagioclase, quartz and garnet are smaller than that which defines the foliation, and may be nucleated grains whose further growth was restricted.

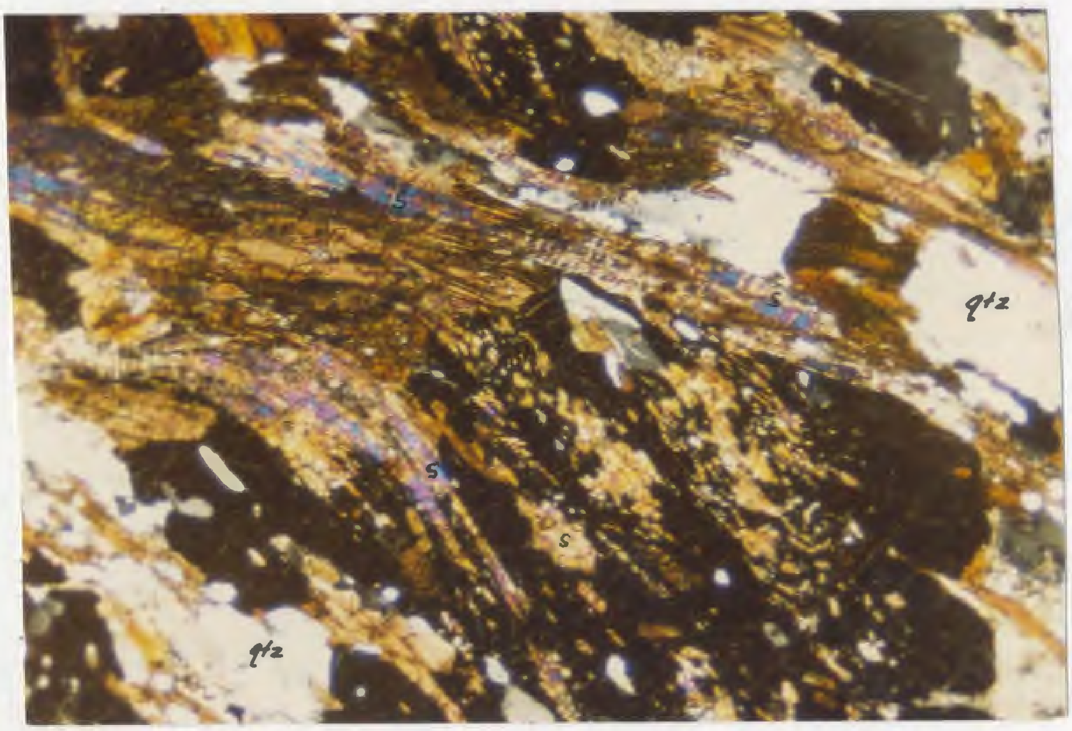
Garnet occurs in all the pelitic and semi-pelitic compositions studied. Two ages are tentatively identified on the basis of microstructural criteria. Well-formed, massive, subidiomorphic to ovoid garnets, up to 1 cm in diameter and with very few inclusions, occur as a pre-tectonic phase, predating the sillimanite-biotite foliation which forms augen around them (Plate 12a). One such garnet contains an inclusion of green tourmaline, an "exotic" mineral not accompanying the present assemblages in any of the rocks studied. This is interpreted to be a relic from an earlier (lower grade?) paragenesis, the tourmaline having formed as a result of boron

PLATE 12

GARNET IN METASEDIMENTS



12a. Pre-tectonic garnet (lower right) augened by biotite-sillimanite foliation. (X 15)



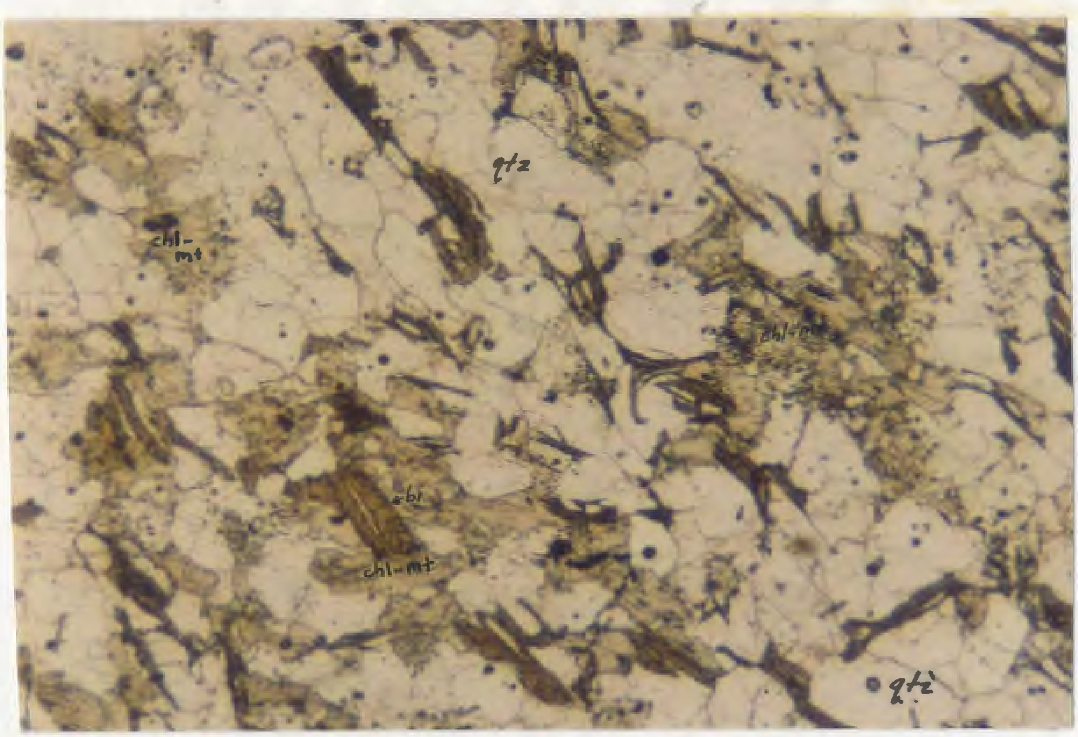
12b. Post-tectonic garnet overgrowing the sillimanite-biotite foliation. Note that sillimanite inside the garnet is smaller than that outside. (X 60) in the clays of the original sedimentary protolith. Biotite and sillimanite are the most common inclusions in garnets of this type.

In contrast to the relatively inclusion-free aspect of the pre-tectonic garnets, a more widespread variety in the pelitic rocks is characterized by a poikiloblastic or seive texture which is interpreted to have resulted from late syn-tectonic or post-tectonic crystallization, during which the garnets overgrew the other phases in the rock. These garnets form large xenomorphic grains or granular clusters up to 1 cm in diameter. The internal foliation (S_i) of the inclusions is generally parallel and continuous with the external one (S_e), but S_i tends to be somewhat finer grained than S_e (Plate 12b). Possible explanations may be that the garnet encroached on its internal constituents, there has been post-garnet coarsening of the external fabric, or the inclusions have been involved in the garnet-forming reaction.

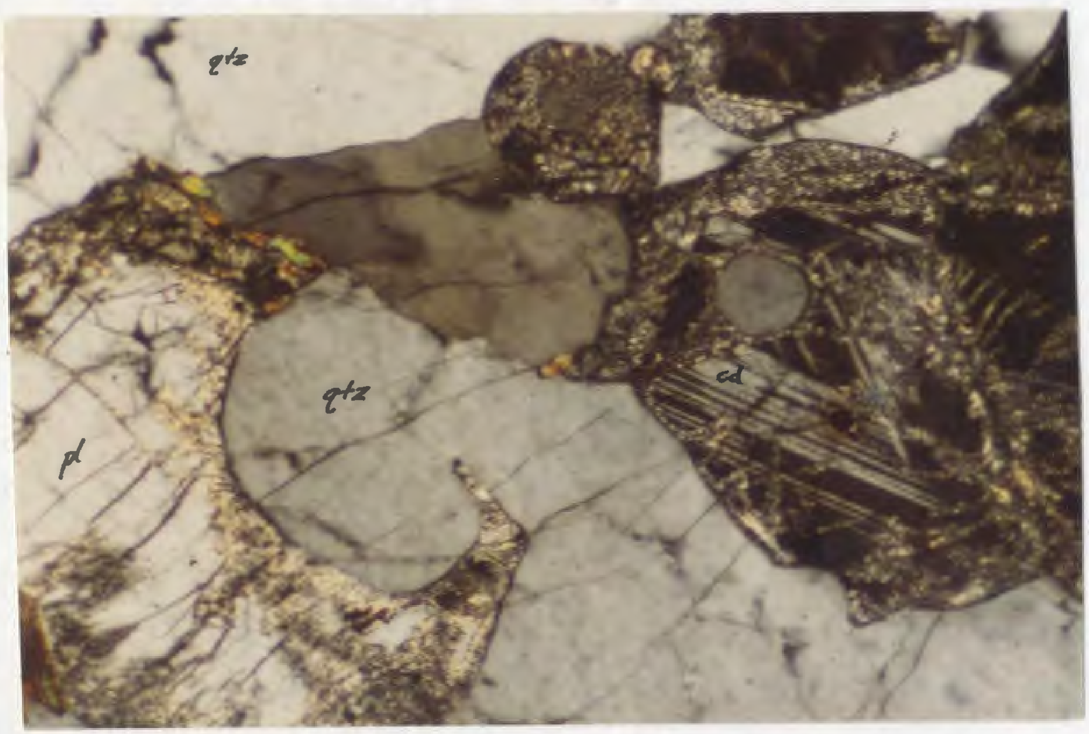
In one rock (38e), a psammitic gneiss, the garnet occurs as xenomorphic, variably-sized poikiloblasts which have been largely replaced by an association of chlorite-magnetite-quartz ± carbonate. These minerals occur in patchy distribution between the other constituents, similar to the granules of garnet, and are therefore interpreted as a retrograde product of the garnet, although no relic garnet remains in either clot (Plate 13a).

PLATE 13

ALTERED GARNET AND CORDIERITE



13a. Chlorite-magnetite clots formed by retrogression of garnet. (X 60)



13b. Twinned cordierite with pleochroic halo around zircon inclusion. (X 60)

Cordierite occurs both as large xenomorphic poikiloblastic porphryoblasts, and as aggregates of interlocking subidiomorphic grains in cordierite-quartz-feldspar layers. It is variably altered to yellowish pinite (muscovite and chlorite; cf. Schreyer, 1958), from minor marginal alteration and penetration by dendritic networks to complete replacement. The least altered grains preserve twinning and yellow pleochroic haloes around zircon inclusions (Plate 13b). In several instances slightly altered cordierite porphyroblasts overgrow the sillimanite-biotite fabric. In others pinitized cordierite follows the foliation wrapping around the pre-tectonic garnets. These features of cordierite habit suggest that its growth began during the formation of the regional foliation, but the crystallization outlasted the deformation.

The quartzofeldspathic component of the metasediments occurs as granoblastic inequigranular mosaics between the oriented growths of biotite-sillimanite which define the foliation. Grain boundaries are straight to sutured; quartz contains deformation bands and misoriented subgrain structures. The influence of mica and sillimanite on grain shape of the quartz-feldspar portions is easily seen when the fabric-forming species are present in significant amounts in the more granoblastic portion of the rocks. Grain boundary growth perpendicular to the foliation is inhibited, the resulting configuration being composed of somewhat rectangular grains of feldspar and quartz with their long dimension oriented parallel to the schistosity.

Twinning in the plagioclase is commonly diffuse, although some grains show wedge-shaped albite twin lamallae of deformation origin. Potassium feldspar (microcline) was observed in two thin sections (11b, 48b) of the pelitic metasedimentary rocks studied. It is not abundant, forming xenomorphic micro-perthitic grains, partially altered to muscovite, between the other constituents.

The calc-silicate rocks have very complex mineral assemblages dominated by calcite and microcline. The carbonate occurs as interlocking xenomorphic grains with straight to sutured boundaries. In contrast to its absence in the pelitic rocks, microcline is ubiquitous in these impure carbonate rocks, forming fresh, polygonal, well-twinned grains averaging 1 × 1 mm in size. It also forms individual bands up to 1 cm thick, associated with zoisite and tremolite; calcite is a minor component in such layers.

The calc-silicates contain abundant xenomorphic grains of zoisite, ranging in size from small blebs, to porphyoblasts > 1 cm in diameter. It displays a very intense "Berlin blue" anomalous birefringence, and contains inclusions of all other phases in the rocks, as well as numerous relics of muscovite, polysynthetic twinning, and narrow coronal overgrowths of clinozoisite are present on some grains.

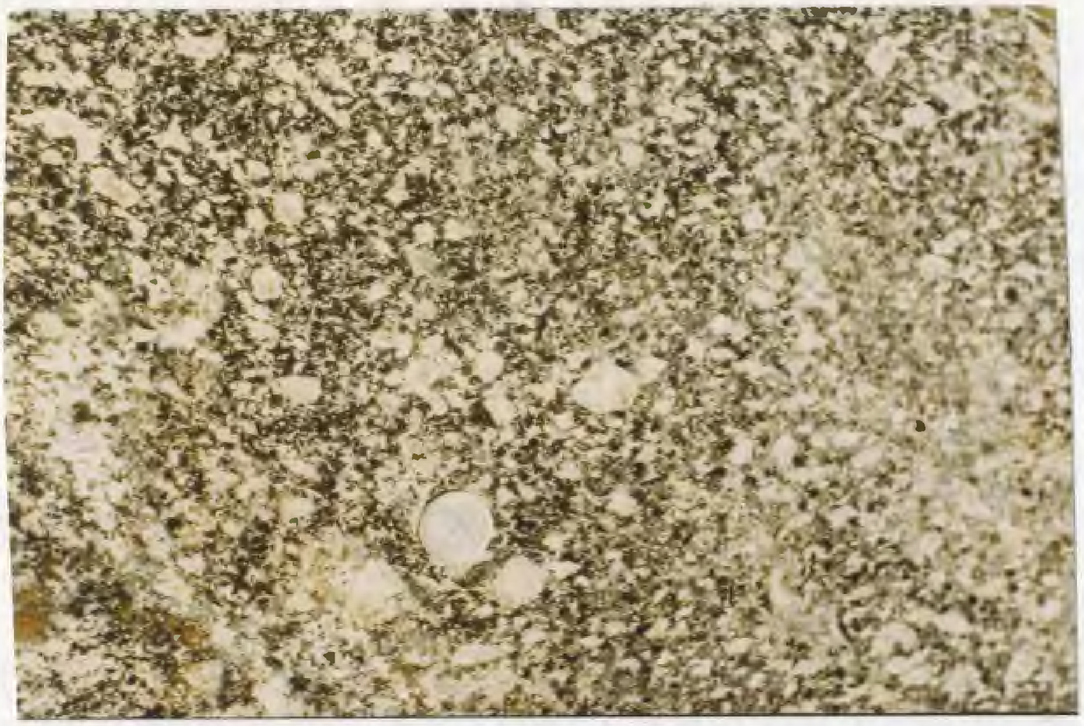
Diopside forms xenomorphic, weakly pleochroic granules (averaging 1 × 1 mm), often surrounded by a rim of tremolite or pargasite. The latter also forms ragged porphyroblasts up to 5 × 2 mm, with the following pleochroic scheme: X = yellow-green, Y = grey-green, Z = dark green.

III. 3. 1a. Metagabbro Sills in Metasediments at Hebron.

On the coast southwest of Hebron village (58°11'10"N; 62°37'40"W) the supracrustals contain intercalated porphyritic, basic rock layers which appear to have been derived from one, or a series of, porphyritic gabbroic sills injected into the metasedimentary/metavolcanic succession. The rocks contain abundant megacrysts of plagioclase up to 5 × 2 cm, some of which appear to retain their original euhedral forms and relic igneous zoning (Plate 14a), and in several exposures there appears to be primary igneous layering preserved due to varying concentrations of coarse feldspars (Plate 14b). These rocks are quite spectacular, and are easily distinguished in the field. Their porphyritic character is a distinctive feature, and they may be useful as marker units for tracing out structures in the supracrustals at this locality. Unfortunately, the inclement weather of the field season prevented the writer from visiting this coastal section other than once, and therefore could not follow-up

PLATE 14

METAGABBRO SILLS



14a. Primary igneous euhderal crystal outlines in plagioclase from porphyritic sills at Hebron (photo normal to lineation).

14b. Anorthositic metagabbro layer in sills at Hebron.

the preliminary mapping.

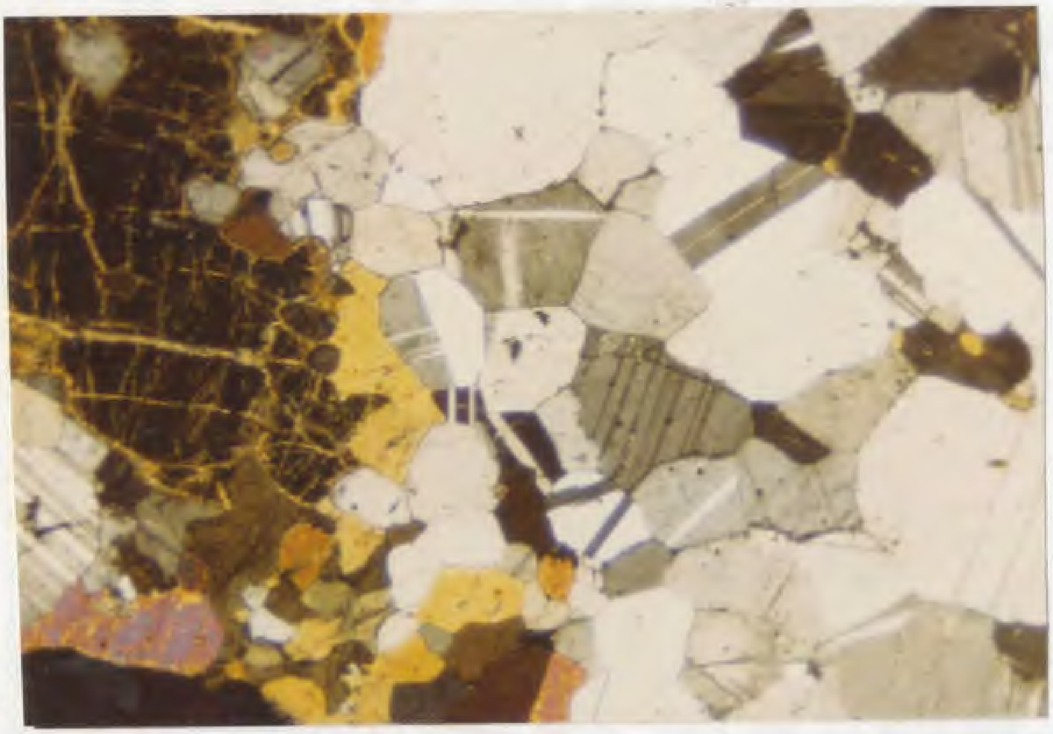
In thin section it can be seen that the feldspar megacrysts which give the rock its distinctive appearance are recrystallized to polygonal aggregates (Plate 15a); the overall microstructure is a granoblastic inequigranular assemblage of hornblende-plagioclase-clinopyroxene-orthopyroxene.

The hornblende occurs as variable sized xenomorphic grains attaining maximum dimensions of 3 × 1 mm, having a strong brown component to its pleochroism (X = buff, Y = greenish brown, Z = brown). Grain boundaries are straight to curved, and its only inclusions are plagioclase and small ragged grains of biotite.

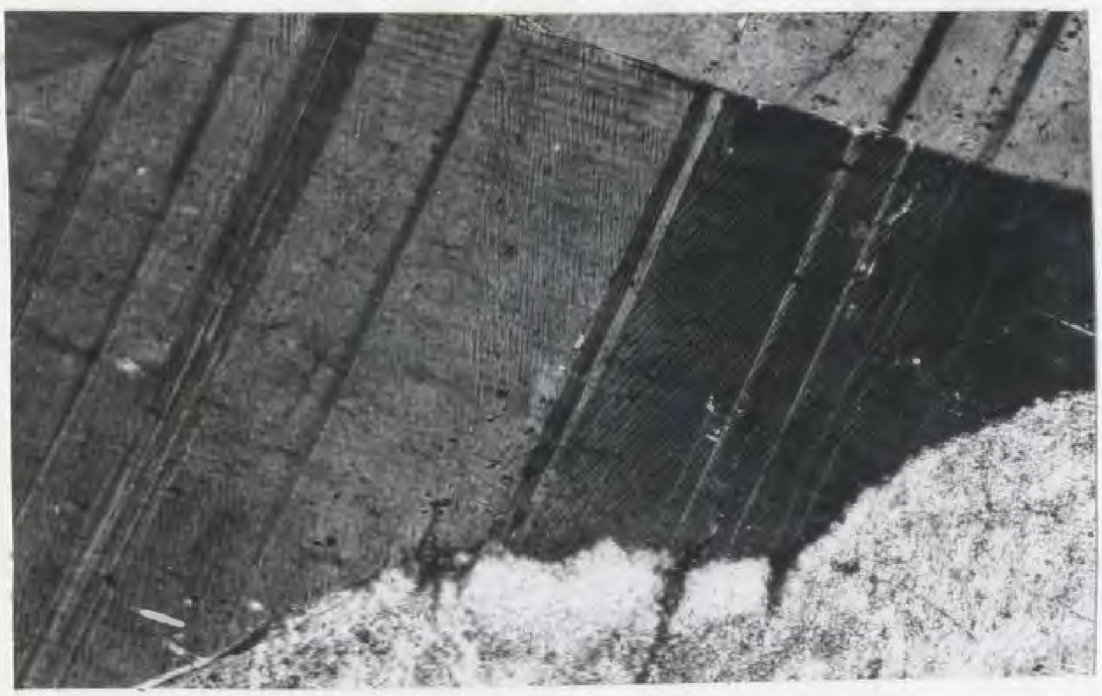
Plagioclase forms very regular polygonal grains with curved to straight grain boundaries, from <0.5 to 3 mm in maximum dimension. Twinning is present in nearly all grains. Though mostly of deformation origin (eg. lenticular wedges) there are some which terminate abruptly within the grains, and according to Vernon (1965, figure 7) are growth twins; very broad simple twins are also interpreted to be of the latter type. The feldspars are more calcic than those from other rocks in the area, being near the middle of the plagioclase series from An_{54} to An_{60}. Many of the plagioclases display a discontinuous pattern of very fine lines whose actual disposition cannot be resolved with the petrographic microscope, but which are tentatively identified as

PLATE 15

PLAGIOCLASE IN METAGABBROS



15a. Aggregate of polygonal grains from a recrystallized metacryst. Orthopyroxene at extinction in upper left. (X 15)



15b. Microantiperthite (or dislocation features?) in plagioclase grain from sills. (X 100) microantiperthite. However they may be very fine dislocation structures. In many adjacent albite twins, these lines have different orientations such that a herring-bone pattern develops (Plate 15b).

Colourless or very pale green xenomorphic grains of clinopyroxene, up to 3 mm in diameter occur throughout the rock, some having narrow rims of actinolite. Its relationship to the hornblende is difficult to access; commonly it occurs on the margins of it, and appears to replace it.

Orthopyroxene, very weakly pleochroic (pink to pale green), has been largely altered to a fibrous orthoamphibole, but also occurs as relatively fresh grains up to 5 mm in diameter. It has a xenomorphic, somewhat ameboid, poikiloblastic form, and encloses both hornblende and clinopyroxene, indicating that it crystallized later than these other two ferromagnesian minerals.

III. 3. 2. The Basic Gneiss Belts.

III. 3. 2a. Nomenclature.

Basic gneisses of the Upernavik supracrustal series have two principal modes of occurrence in the study area. The first is an association of relatively thin units within and bordering the metasedimentary rocks as described in the previous section. A second mode of occurrence of basic gneisses is as thick mappable units in the quartzofeldspathic gneisses, commonly with numerous lenticular ultramafic bodies. Two large units of the latter type occur in the map-area, one on Mt. Jerusalem, and a second stretching from the west arm of Jerusalem Harbour northward to Morhardt Point (See Figure 7).

The term "basic gneiss" is used to cover a suite of metamorphic rocks in which mafic minerals predominate over the felsic constituents. The presence of hornblende, clinopyroxene and orthopyroxene in the rocks has necessitated the use of the following terminology to describe the basic gneisses in the area:

a) amphibolite = hornblende + plagioclase

b) pyroxene - amphibolite = hornblende + plagioclase + clinopyroxene (cpx < hb)

c) clinopyroxolite = clinopyroxene + plagioclase

d) hornblende - clinopyroxolite = clinopyroxene + plagioclase + hornblende (cpx > hb)

e) orthopyroxolite = either of the above assemblages + orthopyroxene (opx(±cpx) > hb)

f) hornblende - orthopyroxolite = same as (e) but opx(±cpx) < hb.

The terms "orthopyroxolite" and "clinopyroxolite" are new terms, introduced to cover the range of rock-types formed by various combinations of plagioclase, hornblende and/or pyroxenes in the basic lithotypes of the map-area. A brief discussion of their use follows.

Orthopyroxolite is a term used to define any metamorphic basic rock with orthopyroxene as a constituent mineral, such that any hornblende present does not exceed the total pyroxene(s), i.e. the hornblende to orthopyroxene (± clinopyroxene) ratio is not greater than 50:50. If hornblende does exceed the total pyroxene(s), then the rock is termed a hornblende-orthopyroxolite. Assemblages therefore which may be encountered are orthopyroxene-plagioclase, orthopyroxene-plagioclase-clinopyroxene, orthopyroxene-plagioclase-hornblende and orthopyroxene-plagioclase-clinopyroxene-hornblende.

The term clinopyroxolite is used to cover metamorphic rocks composed of plagioclase and clinopyroxene. Hornblende may be present, but not exceed the hornblende/clinopyroxene ratio of 50:50; if it does the rock is a pyroxene-amphibolite (see below). If hornblende is present within the limits (i.e. less than clinopyroxene), the rock is termed hornblende-clinopyroxolite. Assemblages covered by this definition are clinopyroxene-plagioclase and clinopyroxene-plagioclase-hornblende.

Amphibolite is defined as any basic metamorphic rock lacking orthopyroxene, and in which the hornblende to clinopyroxene ratio is not less than 50:50. If clinopyroxene is completely absent the rock is simply termed amphibolite; if clinopyroxene is present within the limits above (ie. hb > cpx), then the rock is a pyroxene-amphibolite. If clinopyroxene exceeds hornblende then the rock is a hornblende-clinopyroxolite (see above). Assemblages encountered are thus hornblende-plagioclase and hornblende-plagioclase-clinopyroxene.

It can be seen from the above that if orthopyroxene appears in either the amphibolite or clinopyroxolite assemblages the rock "automatically" becomes an orthopyroxolite (or hornblende-orthopyroxolite depending on the pyroxene(s)/hornblende ratio). These definitions have the advantage that both amphibolites and clinopyroxolites may occur in both amphibolite and granulite facies terranes, but orthopyroxolite can only occur in areas of granulite facies. Therefore by definition, the first occurrence of an orthopyroxolite within an area of progressive metamorphism indicates the onset of PT conditions of the granulite facies, a direct analogy with the criterion of the first appearance of orthopyroxene (Turner, 1968; Winkler, 1974, p.254).

There has been much discussion over the past few years on rock nomenclature in high-grade gneiss terranes. Some of the arguments (pro and con) for various classification schemes may be found in Behr and others (1971) and de Waard (1973). The terminology applied by the author avoids some of the problems involved in orthopyroxene-bearing combinations which are either pyriclasites, hornblende-pyriclasites or pyroxene-amphibolites (Berthelsen, 1960). Under the classification outlined above the presence of orthopyroxene in any amount defines the rock as an orthopyroxolite. Rocks of this type have also been called basic charnockites (Parras, 1958; Cooray, 1962), pyroxene granulites (Subramanium, 1959), basic charnockitic granulites (Evans, 1965), and basic granulites (Singh, 1966). In this thesis the term "granulite" is used in the sense of a metamorphic mineral facies as defined by Eskola (1952) and orthopyroxolite is by definition a granulite facies rock.

It has been pointed out by some authors (cf. Skjernaa, 1973 p.6) that in metamorphic terrains there may occur basic rocks in which clino-pyroxene is in excess of hornblende, but hypersthene is absent. These rocks have been variably referred to as "clinopyroxene-plagioclase rocks", "clino-pyroxene-plagioclase-hornblende rocks" or "pyroxene-amphibolites". It is for these rocks that the writer has proposed the term clinopyroxolite, a name which may be also applied to diopside-plagioclase rocks derived from the metamorphism of calc-silicates, as well as basic tuffs.

III. 3. 2b. Description.

The Mt. Jerusalem and Jerusalem Harbour - Morhardt Point basic gneisses are described below; the contact relationship of the latter with the gneiss is treated in detail. Other variations in the mesoscopic and microscopic character of the basic gneisses are noted briefly by reference to an ultramafic-mafic rock association in Jerusalem Harbour and an orthopyroxolite from Hebron. These descriptions broadly apply to all rocks of this type in the area, including minor units in the gneisses, and continuous units associated with the metasediments. For instance, on the point at the entrance to Jerusalem Harbour an elongate unit of pyroxene-amphibolite occurs, which quickly pinches out northward along strike. This unit and several other small fragmented bodies at this locality contain small pockets or pods of calc-silicate (calcite-diopside-scapolite-sphene) and zoned epidote-garnet-calcite "skarn" rocks. Some of the numerous lens of basic gneiss within the area may well be pre-Uivak in age, but this could not be established with certainty in the field.

(i) The Mt. Jerusalem basic gneiss unit is approximately 0.5 km wide, and can be traced continuously along strike a distance of 2 km. It varies from weakly banded to well-banded, the banded appearance being due to the alternation of bands with varying mineral content (see below). It contains coarse granitic pegmatites forming slightly discordant intercalations on a megascopic scale, but which extensively net-vein and brecciate the body locally. Numerous small ultramafic pods are scattered throughout the central part of the basic gneiss unit.

The western contact with the Iterungnek gneisses is sharp, and the gneisses contain numerous variably sized mafic and ultramafic inclusions derived from the basic gneiss. These inclusions are disrupted and commonly extremely attenuated.

The Mt. Jerusalem basic gneiss body interdigitates with heavily remobilized Uivak gneiss and sheets of syntectonic, white weathering, weakly foliated granite which it abuts along strike. Large, oriented basic gneiss and/or ultramafic inclusions form easily mappable "mega-xenolithic" zones within these gneisses/granite sheets. A tight synformal closure is present on the coast to the East of the southern extremity of the basic unit. It is fault-bounded, but appears to represent an original hinge zone of the body which has been transposed by later faulting.

The mesoscopic variation in the character of the Mt. Jerusalem basic gneiss has its counterpart in the mineralogy. The assemblage hornblende-plagioclase-orthopyroxene-clinopyroxene is present in the massive rock, whereas hornblende-plagioclase-clinopyroxene dominates the banded portion. In thin section the banded appearance is seen to be due mainly to bands of clinopyroxene-plagioclase alternating with bands of clinopyroxene-plagioclase-hornblende. The banded portions are devoid of orthopyroxene, which is surprising since the massive portions contain orthopyroxene far in excess of clinopyroxene.

The massive portion, a hornblende orthopyroxolite, is characterized by a granoblastic microstructure. Hornblende and plagioclase are similar in size (av. 1 x 1 mm); orthopyroxene and clinopyroxene are generally smaller. Orthopyroxene tends to form subidiomorphic tabular grains, elongate parallel to the weak foliation in the rock. Its average size is 0.5 x 0.2 mm, but some grains are greater than 1 mm in length.

The hornblende (X = pale yellow, Y = brownish green, Z = greenish brown) is xenomorphic to subidiomorphic; elongate grains dominate, having a maximum dimension of 3 x 1 mm. Grain boundaries with all species including itself vary from straight to smoothly curved to gently embayed, the latter against feldspar.

The plagioclase (An_{32-36}) is comparable to hornblende in size and form. It is twinned, with wedge-shaped, lenticular, needles (glide twins) being most prevalent. Even though albite twinning dominates the feldspar, combinations according to the albite-pericline laws are not uncommon. These combination twins show many features described by Vernon (1965), eg. albite twins impinging on wider periclines and not appearing on the other side, twins tapering into each other. By analogy with Vernon's investigation, these are considered deformation features. Hornblende and orthopyroxene inclusions occur in plagioclase, the former being ovoid, the pyroxene being subidiomorphic with a few straight crystal faces.

The orthopyroxene, as stated above, is present as tabular grains parallel to the foliation. It is a pleochroic pale green to pink hypersthene, which displays sharp straight or curved interfaces with the other phases present. Sharp boundaries of this type against the hornblende indicate that the two are microstructurally compatible in this rock; there is no evidence that one formed at the expense of the other.

Clinopyroxene is present in the massive rock but is more of an accessory constituent than a major rock-forming mineral. In the banded rock however, it exceeds hornblende, and the rock is a hornblende clinopyroxolite. The banded rock is characterized by plagioclase-clinopyroxene horizons alternating with clinopyroxene-plagioclase-hornblende zones. The bands, averaging 2-5 cm in thickness have a granoblastic inequigranular microstructure, the feldspar having the largest grain size.

Hornblende in the banded basic rock also has a xenomorphic form, but rather than having smooth grain boundaries, it has a more ragged appearance. Also, in contrast to the massive rock, the amphibole has a more pronounced pleochroism exhibiting the following absorption scheme: X = gold, Y = dark green Z = "dirty" greenish brown. There is no evidence to indicate unequivocally that the hornblende has resulted from previously existing pyroxene(s). It rarely partially encloses clinopyroxene, and contains small inclusions of the same, but grain boundaries are sharp and well-defined in most instances.

The plagioclase is microstructurally similar to that of the massive rock except that it is slightly more calcic, in the range An_{36} to An_{42}.

Clinopyroxene is abundant in the banded rock. It is a pale green, weakly pleochroic diopside(?) with a xenomorphic form. The average grain size is <1 mm in maximum dimension, but a few larger grains are present up to 2.5 x 2 mm.

(ii) The basic gneiss unit stretching from the western arm of Jerusalem Harbour to Morhardt Point has intercalated with it a long, narrow sheet of quartzofeldspathic gneiss and a thin wedge of metasediments. Both of these narrow units within the basic rock pinch out southward along strike from Morhardt Point.

The basic gneiss is a black, equigranular, fine to medium grained rock. Its appearance varies from massive granoblastic to well-banded. The banding is commonly streaky, as a result of the presence of discontinuous "stringers" of feldspar in the plane of the foliation (Plate 16a). Although hornblende and plagioclase are easily identified in hand specimen, irregular granular garnet and pale green clinopyroxene are also unevenly distributed throughout the rock. Under the terminology outlined previously, the rock is termed a garnetiferous pyroxene-amphibolite. Locally, especially on the shore of Jerusalem Harbour the basic gneiss contains irregular pods and discordant veins of quartz-feldspar-orthopyroxene pegmatite (Plate 16b). These

PLATE 16

BASIC GNEISSES

16a. Streaky banding of quartz-feldspar stringers in pyroxene amphibolite. North shore of Jerusalem Hr.

16b. Irregular pyroxene(brown)-bearing pegmatites. Same locality as above.

pegmatites are restricted to the basic gneiss at this locality, and may be "sweats" expelled during high grade metamorphism, or else the result of some metasomatic processes. No such pegmatites were found in the quartzofeldspathic gneisses adjacent to the pyroxene-amphibolite, and no orthopyroxene has been observed in the groundmass of the basic gneiss except directly adjacent to the pegmatites themselves.

Petrographically, the basic unit contains hornblende-plagioclase-clinopyroxene-garnet; adjacent to the orthopyroxene-bearing "sweats" orthopyroxene appears in the groundmass of the basic rock and clinopyroxene disappears. Overall, the morphological characteristics of the constituent minerals is similar to those described for the Mt. Jerusalem basic gneiss.

The chief mineral is a brownish hornblende (X = yellow green, Y = green brown, Z = brown) forming xenomorphic grains averaging 2 x 2 mm in size. Triple-point junctions are developed at the interfaces between its straight to gently curved grain boundaries; plagioclase is its only inclusion.

The plagioclase in the rock is andesine (An_{36-40}). It has the usual twinning features, but in addition has narrow marginal zones which are untwinned. It is locally altered to carbonate; pyroxene is its only inclusion.

Clinopyroxene occurs as pale green, non-pleochroic granular grains, usually < 1 mm in dimension, but up to 2.5 x 1 mm. Its grain boundary relationships with the other constituents vary from curved to serrated; narrow coronas of actinolite are locally developed.

Garnet has a poikiloblastic porphyroblastic form, elongate (up to 5 mm) within the foliation.

Adjacent to the pegmatoid patches, clinopyroxene is absent, and orthopyroxene appears in the rock. This could either be due to a breakdown of hornblende (and/or clinopyroxene?), or be a metasomatic growth. The orthopyroxene forms xenomorphic and subidiomorphic tabular grains up to 3 mm in length enclosing hornblende. It is commonly altered to a very fine-grained, highly birefringent mineral (sericite?). The hornblende in these areas changes slightly in pleochroism to X = buff, Y = brownish green, Z = brown.

The pegmatite patches in the rock are composed of coarse-grained, intensely pleochroic hypersthene, ameboid quartz and polygonal plagioclase.

The northern extension of this pyroxene amphibolite unit has been studied along the coast approximately half-way between Jerusalem Harbour and Morhardt Point (Figure 8). The western contact with the gneisses is very irregular (i.e. undulating) on a small scale, but the banding in the gneisses follows the contact and with only one exception (see below), is not discordant to it. The basic rock is brecciated and is net-veined by leucocratic veinlets from the gneisses, and later granite pegmatites. In the banded gneisses a second biotite foliation crossing the main fabric can be demonstrated, and an intersection

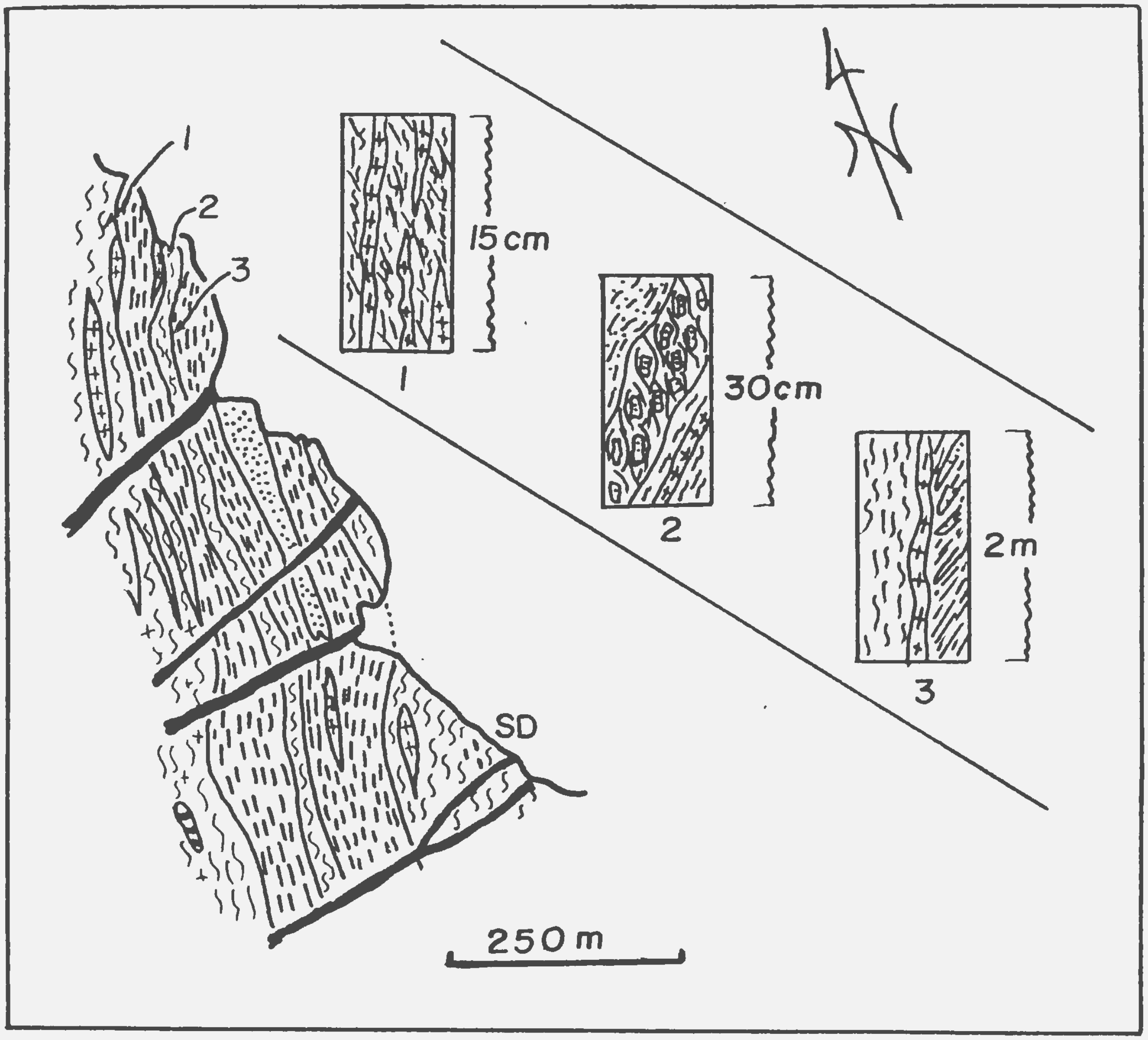


Figure 8. Sketch-map to show relationship between pyroxene-amphibolite and quartzofeldspathic gneiss on the coast of Morhardt Point.

<u>Legend</u> a) wavy lines and crosses = gneisses and granite sheets, somewhat diagrammatic
b) broken lines = pyroxene-amphibolite
c) dots = metasediments
d) crosses = pegmatites
e) cross-hatched = ultramafic pod
f) solid thick lines = diabase dikes
g) SD = Saglek dyke remnants in gneisses

Insets show relationships described in the text

1. Cross-cutting foliations in reworked gneiss
2. Anastamosing biotite fabric in pegmatite separating amphibolite (upper left) from gneiss (lower right)
3. Discordant contact between banded gneiss (left) and pyroxene-amphibolite (right).

lineation plunging vertically is visible on some gneissosity planes. The gneisses, which contain thin homogeneous concordant granite sheets, are regarded as slightly reworked Uivak gneisses. The veinlets which penetrate the amphibolite from the gneisses display a fabric which parallels the second foliation in the gneisses. This fabric is not seen in the basic gneiss because of the mineralogical character of the rock.

The contact between the central gneiss unit within the pyroxene amphibolite and the basic rock is locally followed by a coarse, augen-textured pegmatite up to 0.5 m wide. The augen texture is the result of biotite flakes wrapping around lozenge-shaped "eyes" of feldspar. The foliation thus formed is oblique to the margins of the pegmatite but is parallel to the second foliation in the gneisses described above. The central gneiss unit is a grey, biotite foliated rock, lacking an extensive interlayered pegmatite component. It resembles the Uivak gneisses; however no Saglek dykes were recognized within it.

A thin wedge of metasediments within the basic gneiss, (Figure 8) is composed of rusty weathering garnetiferous semipelites, cordierite-bearing pelitic units with blue, pinitized cordierite porphroblasts up to 1.5 cm in diameter, garnet-sillimanite-quartz-biotite rocks, fine-grained biotite-quartz-feldspar-graphite semi-pelites, and very thin lens (< 30 cm thick) of well-banded light to dark green amphibolite (meta-tuffs?).

The banded gneiss sheet within the pyroxene amphibolite can be shown to be in tectonic contact with the amphibolite near its northernmost extension on Morhardt Point (Figure 8). The contact between the amphibolite and the gneisses is markedly discordant, but this relationship only exists for ~5 m along strike, with concordant relationships between gneissosity and amphibolite banding elsewhere. At the locality in question the banded amphibolite (which strikes 020 and dips steeply to the NW) contains very tight isoclinal intrafolial folds whose axial traces have been warped by later open folds. A foliated biotite pegmatite (biotite alignment striking 012) separates the amphibolite from the gneiss, the banding in the latter nearly paralleling that in the pegmatite (strike 018; dip 85 NW). This relationship is interpreted as representing a contact along which a previously foliated amphibolite has been tectonically transposed against the gneisses. It is not possible to state with certainty at present whether this discordance is a relic from the early interleaving of the Uivak gneisses and the Upernivik supracrustals, or whether it developed during the remobilization of the gneiss terrain 500 million years later. If the grey gneiss sliver in the amphibolite is Uivak gneiss, then it may be remnant of the early tectonism which has been preserved.

(iii) Approximately half-way into Jerusalem Harbour (58°13'50"N; 62°37'40"W) there occurs an ultramafic/mafic rock assemblage in which ultramafic rocks (to be described in III.4) apparently have a transitional contact with orthopyroxene-bearing homogeneous and foliated basic rocks. The rock types and relationships have led to the conclusion that the sequence represents part of a layered complex which has been modified by metamorphism and deformation. The basic rocks, orthopyroxolites, have probably been derived from gabbroic parents. They vary from dark-green to black in colour for the most mafic-rich, to pale brown and green-grey in the felsic varieties; garnet is conspicuous in nearly all rock types, occuring as granular aggregates in plagioclase-rich clots. The basic rocks locally display textures which resemble deformed cumulates, in which the feldspars have been streaked out in the plane of a fabric which is axial planar to tight folds in the nearby gneisses. Features interpreted as primary igneous textures modified by deformation also occur in the ultramafic rocks (III.4).

Several basic rocks regarded as being derived from gabbroic protoliths have been studied petrographically. The assemblage hornblende-plagioclase-clinopyroxene-orthopyroxene-garnet ($\pm$quartz) is common to all. The microstructure is granoblastic inequigranular; the shape of the grain boundaries between adjacent grains depends on the forms of the two constituents, and varies from straight to sutured.

Hornblende is the chief mafic phase. It occurs as pleochroic (X = pale brown, buff; Y = green; Z = greenish brown, dark brown), xenomorphic grains with a maximum size of 3 x 1 mm. Grain boundaries are dominantly curved, and some marginal alteration to a greenish blue amphibole has been noted, especially where it is in contact with actinolite (after clinopyroxene).

Fresh plagioclase (An_{34-42}) forms polygonal grains up to 4 x 4 mm, with curved to straight grain boundaries, except against quartz, which embays it. It may show high dispersion, twinning is as usual, and amphibole and quartz are its major inclusions.

Both clinopyroxene and orthopyroxene occur together as xenomorphic granular clusters throughout the rocks; individual grains rarely exceed 1 mm in size. Both show minor alteration to green hornblende and actinolite, but microscopic evidence indicates both pyroxenes are in stable co-existance with the brownish hornblende.

Garnet occurs either as ovoid grains up to 8 mm in diameter surrounded by a narrow mantle of polygonal plagioclase (Plate 17a), or as small irregular granules in plagioclase patches. It is in direct contact with all other phase except orthopyroxene, suggesting that garnet and orthopyroxene are incompatible in this assemblage. The significance of the garnet-plagioclase-orthopyroxene relationship is considered in the next chapter in the discussion of the metamorphism of the basic rocks.

(iv) The final basic gneiss to be described is an orthopyroxolite from the supracrustal succession on the shore near Hebron village. It is a foliated, brown-weathering rock consisting of orthopyroxene, plagioclase, and hornblende.

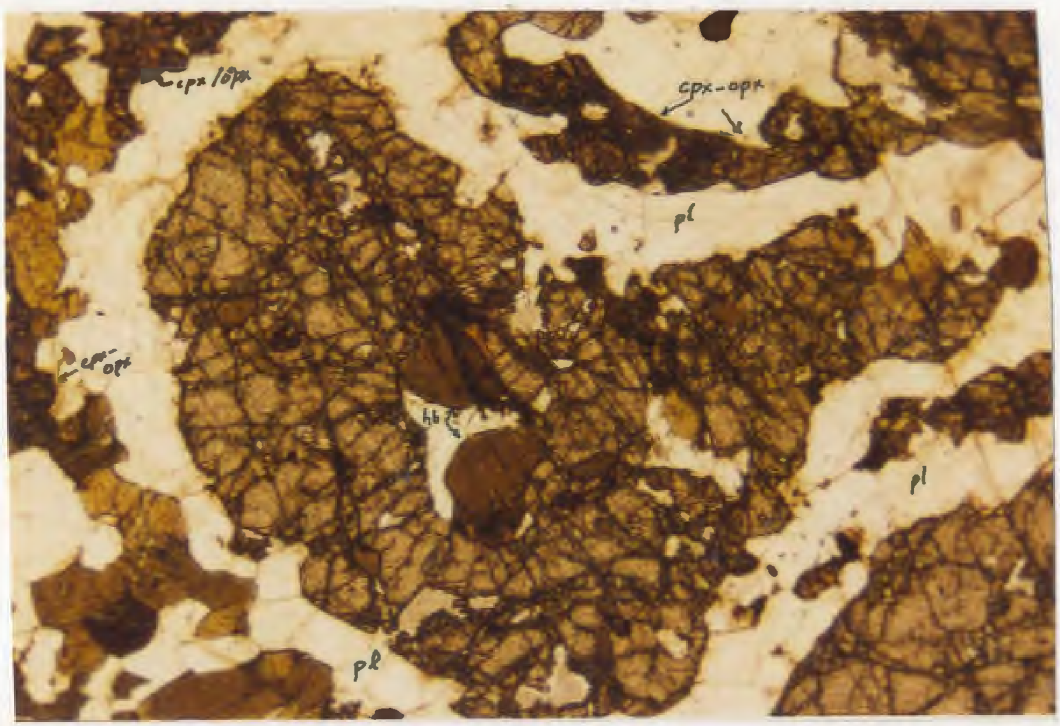
Colourless orthopyroxene forms elongate grains up to a centimeter in length defining the foliation. It has curved grain boundaries, and contains ovoid inclusions of hornblende and plagioclase. It is locally altered to a fine-grained matted colourless amphibole (?).

The plagioclase grain-shapes are controlled by the larger pyroxene and amphibole, therefore characteristic shapes are xenomorphic with rounded boundaries, rarely exceeding 1 mm in size. Microantiperthite is present similar to that of the feldspars in the metagabbro sills, but not as well developed, occurring as patches in individual grains. Although compositions between An_{50} and An_{54} dominate, more sodic varieties (e.g. An_{36}) have been observed. Some grains show reverse zoning, from a sodic core (An_{46}) to a more calcic margin (An_{60}), a feature common in some metamorphic rocks (cf. Phillips, 1930; Misch, 1954; Barth, 1956). In these zoned feldspars the sodic center is antiperthitic, the rims are devoid of it.

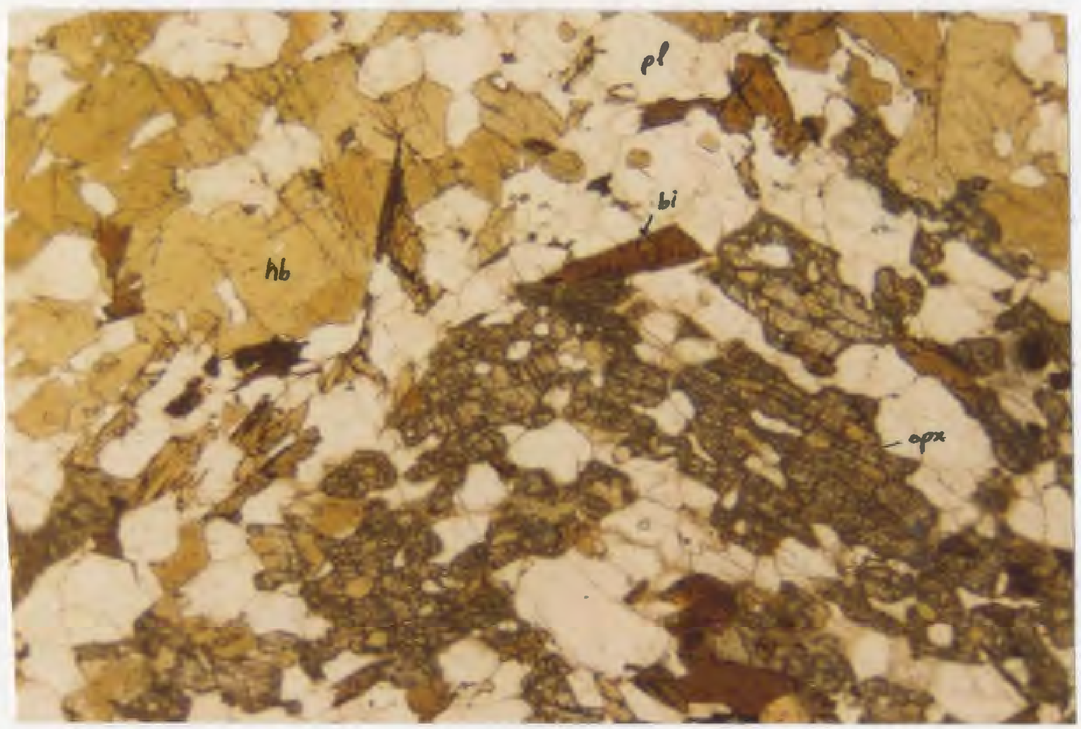
Hornblende forms strongly pleochroic (X = pale yellow, nearly colourless, Y = light greenish-brown, Z = yellow-brown) xenomorphic elongate grains up to 3 × 1 mm in size,

PLATE 17

GARNET AND ORTHOPYROXENE IN BASIC GNEISSES



17a. Plagioclase corona around garnet in orthopyroxolite from Jerusalem Hr. (X 15)



17b. Folded orthopyroxene fabric in orthopyroxolite from Hebron. Brown hornblende-rich band at top. (X 15) which, with orthopyroxene, defines the foliation. Even though pyroxene contains inclusions of hornblende, the converse is not true.

The orthopyroxene-bearing fabric in these rocks has been isoclinally folded, but generally these folds lack any axial planar schistosity (Plate 17b), except for the reorientation of a few grains of accessory biotite, which otherwise follows the foliation around the nose of the fold.

III.4 The Ultramafic Rocks

Rocks of ultramafic composition (< 30% felsic minerals) are scattered throughout the study area. They have three modes of occurrence, viz. within the basic gneisses, at the margins of the basic gneisses separating them from the quartzofeldspathic gneisses, and (rarely) as bodies completely surrounded by the granitic gneisses. Although most contacts are considered to be of tectonic origin, there is one occurrence where there appears to be a gradational contact between the mafic and ultramafic rocks, as pointed out in the last section. The ultramafic rocks of this association are described below. The petrology and structural setting of some of the ultramafic rocks provided the basis for an undergraduate honors thesis by Martin (1976). The following descriptions are augmented by his project.

The ultramafic rocks occur as linear lensoid bodies rarely exceeding 300 m in length and 75 m in width; the majority are sub-rounded pods and lens on the order of 50 × 20 m. They commonly form megascopic inclusion trains devoid of contact aureoles, confined to narrow horizons and concordant with the surrounding gneissic banding. This suggests that they represent the secondary expression of tectonically disrupted primary continuous sheet-like intrusions. The present boundinaged form is probably due to the ductility contrasts between the ultramafic and the surrounding rocks during deformation.

The ultramafic rocks are easily identified from a distance in the field by their orange, brown, and rusty-red weathering colours (Plate 18a) which in turn is governed by the mineralogy, e.g. presence of pyroxenes, amount of serpentinization.

Rocks which preserve indications of their primary mineralogy are rare, although there is evidence to suggest that some compositions are recrystallized primary constituents. The present mineral assemblages suggest that the primary lithologies were dominated by dunite, websterite, pyroxenite and possibly wehrlite (classification of IUGS Subcommision, 1973). A pale green pleochroic amphibole (edenite?) is the most common hydrous mineral found in these rocks.

The mesoscopic structure of the ultramafics is varied. Some are massive, dense, fine-grained rocks, lacking any planar or linear fabrics; others are porphyritic, or consist of

PLATE 18

ULTRAMAFIC ROCKS

18a. Typical rusty red weathering colour of ultramafic rocks.

18b. Orthopyroxene cumulate in layered succession, Jerusalem Hr.

numerous clots or aggregates of pyroxenes up to several centimeters in diameter in a finer groundmass, which when deformed and streaked out give rise to a finely banded rock. Still others are very coarse-grained, have a "knobby" appearance and strongly resemble accumulations of pyroxene (and olivine?) found in undeformed differentiated ultramafic intrusions. An irregular blotchy appearance exhibited by some of the ultramafics also resembles a cumulate texture, and in others there appears to be a systematic variation in grain size of the mineral constituents of individual bands.

The ultramafics are occasionally transected by coarse-grained veins, up to 5 cm in width of talc-actinolite ± pyroxene. Where quartzofeldspathic pegmatites from the adjacent acid gneisses intrude the ultramafics, a narrow zone (up to 30 cm wide) of biotite, formed by metasomatic alteration of the ultramafic, is developed.

The above descriptions give the main field characteristics of the ultramafic rocks. Although most bodies are isolated pods having tectonic contacts with the surrounding gneisses, one ultramafic body on the west shore of Jerusalem Harbour, as mentioned before, has a gradational contact with the associated basic rocks, and the complex is interpreted as part of a layered intrusion.

The ultramafic rocks in this association are somewhat unique in that they are interpreted to have retained some aspects of their original textures despite deformation and metamorphism. Coarse knobby rocks are interpreted as recrystallized pyroxene cumulates consisting of bronze-coloured orthopyroxenes in a dark hornblende-biotite groundmass (Plate 18b). Spinel-rich layers, crossed by a biotite schistosity, also appear to represent a primary feature. Also (the base of?) one layer shows the existance of a branching "birds-foot" array of platy olivines similar to harrisitic textures reported in some cumulate-textured rocks (Plate 19a; cf. Wadsworth, 1961; Donaldson, 1974). Collerson, Jesseau and Bridgwater (1976b) have recently described ultramafic rocks from near Hopedale which they consider may exhibit modified harrisitic growths. Other textures preserved which are reminiscent of a primary igneous origin are small scale folds within layers which appear to be slump-folds, and a coarse blotchy texture similar to that found in other cumulate rocks (Plate 19b; compare with leucogabbro texture in Windley, Herd and Bowden , 1974, Figure 22). The ultramafic rocks appear to have a gradational contact with the associated orthopyroxolites, the transition zone consisting of flattened cumulate textured ultramafics passing upward into garnet-hornblende rocks, which with increasing plagioclase content grade into rocks interpreted as meta-melagabbros and leucogabbros. These features lead to the conclusion that the succession of rocks at this locality represent part of an ultramafic/mafic layered intrusion which intruded the gneisses

PLATE 19
PRIMARY TEXTURES IN ULTRAMAFIC ROCKS

19a. Harrisite-like branching olivines.

19b. Metacumulate texture preserved in pyroxene-bearing layer.

at sometime early in their history.

III. 5. The Iterungnek Gneisses.

This is the name proposed for, and used herein, to designate any quartzofeldspathic gneiss not intruded by the Saklek dykes, and which locally can be shown to be derived by remobilization of the earlier Uivak banded gneisses. Detailed descriptions of the observed relationships between the Uivak gneisses and the Iterungnek gneisses in zones of progressive reconstitution are presented elsewhere in the thesis (Ch. V). The Iterungnek gneisses, do however, contain many syntectonic, foliated sheets of granite (s.l.) and tonalite/ diorite which vein and disrupt the older lithologies. The Iterungnek gneisses are the lithological equivalents of the "undifferentiated gneisses" of Bridgewater et al., (1975) and Collerson et al., (1976 a).

The Iterungnek gneisses are very heterogeneous in their field expression. They are composed of rocks, varying from reworked Uivak gneisses in which the early gneiss is only slightly modified, to "streaky gneisses" characterized by abundant pink potash feldspar and intrafolially folded Uivak enclaves, to "lit-par-lit" gneisses characterized by narrow discontinuous septa of grey gneiss separated by coarse granitic pegmatite, to nebulite or ghost-structure gneiss in which only whisps of the original layering are detected. The suite has a variety of weathering colours - white, pink, pale green, and brownish-yellow when significant biotite is present.

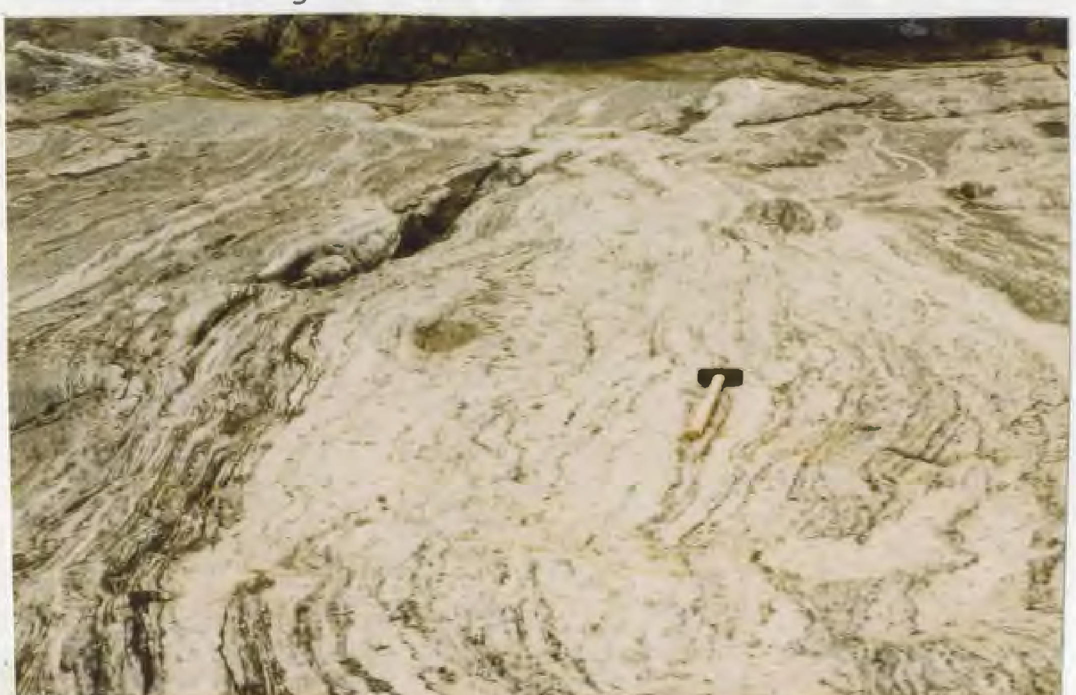
In the potassium feldspar (microcline) rich "streaky gneisses" it is possible to recognize small lenticular zones (eg. 5 x 0.5 m) of grey gneiss considered to be Uivak enclaves. These are intensely deformed however, the enclaves possessing a folded compositional banding and numerous rootless intrafolial folds. The transposition of the Uivak layering leaving only rootless structures is a result of high ductility and shearing during progressive reworking. The gneissosity in the grey gneiss remnants is usually discordant to that of the pink-weathering rock in which it occurs; two cross-cutting schistosities can be observed in the discordant enclaves. The enclaves appear to have undergone some degree of flattening during deformation. Concordant pegmatite veins in the "streaky gneiss" which branch across the Uivak enclaves are tightly folded; the folds have axes which parallel those in the enclosing gneiss. The "streaky gneisses" display a strong lineation on gneissosity planes as a result of feldspar or quartz rodding and quartz-feldspar segregations.

There are other areas where static transformation of the Uivak gneisses appears to have been dominant over a structural reconsitution. Rocks formed in this way are best termed "lit-par-lit" acid migmatites in which thin (10-30 cm) semi-continuous linear layers of modified Uivak gneiss occur between coarse pegmatitic granitic units of similar thickness (Plate 20a). These lit-par-lit gneisses are transitional

PLATE 20

ITERUNGNEK (REMOBILIZED UIVAK) GNEISSES

20a. Development of Iterungnek gneiss by lit-par-lit injection into Uivak gneiss.



20b. More extreme case of 20a. Note whispy layering in nebulite zone.

into more leucocratic fractions in which only ghost-banding remains defined by whispy concentrations of biotite (Plate 20b). The foliation in these nebulitic rocks is defined by irregular linear concentrations of mica. The nebulites locally contain areas of microcline porphyroblasts up to 2 cm in diameter, rimmed by biotite. They appear to be a result of syn-anatectic porphyroblast growth probably as a result of K-metasomatism.

Irregular and linear pegmatitic and granular granitic areas having gradational and indistinct contacts with the enclosing gneiss are often observed in the lit-par-lit gneiss and nebulite areas (Plate 21). These granitic segregations occasionally have a green blotchy appearance due to clots of green biotite which surround a core of brownish mafic mineral. In thin section this brownish mineral is seen to be an aggregate of colourless bladed amphibole.

Features such as these "sweat" pegmatites, the porphyroblast growth and the continuation of gnessic banding into nebulite zones until it becomes progressively obliterated suggests that in situ anatexis may have occurred in such areas. Amphibolite inclusions in these gneisses rarely exhibit relic Saglek dyke textures in the cores, though marginally transformed to massive hornblendite. Close examination of the foliated gneiss portion of the lit-par-lit migmatites reveals a biotite growth crossing the gneissosity

PLATE 21

DIFFUSE PEGMATITES IN ITERUNGNEK NEBULITE

21a,b. Two photos showing blotchy diffuse sweat pegmatites in Iterungnek gneisses
(a) Transgressive, with diffuse contacts,
(b) Closeup of contact.

and an earlier biotite foliation. The orientation of this biotite growth is expressed in the pegmatoid layers as a weak alignment of the quartz, feldspar and biotite in them.

Extensively reconstituted, but weakly foliated gneisses and nebulites are commonly difficult to distinguish from the weakly foliated intrusive granite sheets, both being medium-grained, pink to white weathering rocks.

A relatively structureless granitic portion of the Iterungnek gneisses occurs on the hill forming Morhardt Point. It is a pale-pink to greyish-white weathering granodiorite, containing rare xenomorphic garnet, which inland appears to interfinger with reworked Uivak gneiss. The same rock outcrops on the seacoast at Morhardt Point as a concordant sheet with a simple foliation, intruding migmatitic and complexly structured Uivak gneisses containing rotated Saglek dykes. The contrast between the two rocks is very marked at this locality - complex, banded migmatites with numerous amphibolite inclusions, and the younger homogeneous, weakly foliated grey granodiorite lacking a gneissosity or inclusions.

Inland on Morhardt Point, the foliated granite sheet contains numerous inclusions of amphibolite and ultramafic rocks, which have been "stoped" from a more continuous basic horizon (see Figure 7, p.). These blocks commonly elongate and lying in the plane of the weakly developed foliation, form a mappable agmatite horizon approximately 1.5 km in length. The blocks are derived from a massive unit of amphibolite which outcrops on the shore of Morhardt Point at the entrance to Iterungnek Fiord.

A similar agmatite horizon composed of various sized blocks of basic gneiss and ultramafic material in a weakly foliated, often homogeneous, equigranular, white-weathering granite occurs on Mt. Jerusalem. The basic gneiss unit described earlier, dies out southward along strike as it interfingers with the Iterungnek gneisses. The gneisses vein, brecciate and disrupt the basic gneiss until its final expression is as abundant rafts in the weakly foliated rock.

Metasedimentary gneisses from the supracrustal sequence in the western part of the map-area similarly occur as large rafts in foliated Iterungnek gneisses (see geological map in pocket). Sheets of foliated granite intrude the supracrustals and cut across lithological boundaries within them; net-veining of the rafts is a very prominent feature.

The inclusions of basic gneiss and metasedimentary gneiss behave somewhat differently to the stresses which gave rise to the foliation in the Iterungnek gneisses. Inclusions of the basic rocks occur as competent, sub-angular to lensoid smooth-edged bodies, while the metasediments have been attenuated and occur as granite-streamed stringers flattened within the plane of the foliation. The variable response of the inclusions to the deformation illustrates the extent to which constituent mineralogy affects the ductility of the rocks, the hornblende-bearing basic fragments being more competent than the biotite-rich metasediments (cf. Coward, 1973, p. 144). Rarely, small fragments of basic gneiss are strung out as continuous inclusion trains which, when completely reconstituted lead to narrow lensoid zones of hornblende-bearing granitic gneiss which quickly die out along strike.

Thus, rocks which constitute the Iterungnek gneisses vary from streaky foliated tectonites with Uivak enclaves, to anatectic nebulites with only ghosts of the layering preserved, to intrusive foliated granite sheets. Such variations may occur over distances of a few meters, and are not always apparent in the lichen-covered inland outcrops.

The petrology of the slightly modified Uivak gneisses which form enclaves in the Iterungnek gneisses has been incorporated into the previous descriptions of these early rocks and need not be repeated in detail here. Only a few features relevant to the formation of the Iterungnek gneisses will be mentioned. For example, it was shown that the biotite foliation crossing the compositional banding of the Uivak enclaves differs from the earlier Uivak biotite in that it lacks the oriented rutile needles. The green elongate blebs which form the axial plane foliation to folds in slightly reconstituted mafic members of the Uivak series were identified as actinolite replacing an earlier clinopyroxene.

Aggregates of colourless bladed amphibole in the same rocks may be pseudomorphs of orthopyroxene, similar to those to be described below. Blebby melts in Uivak gneisses which are interpreted to be a result of the Iterungnek event contain a blue-green hornblende, which has been largely replaced by a stellate growth of acicular green biotite and quartz.

The petrographic descriptions presented below apply to the most widespread lithotypes among the Iterungnek gneisses. Firstly, the petrology of the "streaky gneisses" which enclose Uivak relics will be described. This is followed by the lit-par-lit migmatites in order to show how the Uivak compositional banding has been modified by in situ transformation. The petrological features of nebulitic or ghost-structure gneisses from such zones, and the diffuse sweats which occur in them are also described. The section concludes with descriptions of the petrology of the granite sheets which occur on Morhardt Point and intrude the Mt. Jerusalem basic gneiss.

Compositionally the Iterungnek gneisses are not distinctive from the older Uivak suite, the original partitioning of the two being a difference in their mesoscopic character and the mutual field relationship between the two. One striking microscopic feature of the Iterungnek gneisses however is that they appear to exhibit the effects of a retrogressive period of metamorphism more extensively than the Uivak gneisses. This is especially apparent in the almost invariable alteration of plagioclase to granular epidote and sericite, making compositional determinations impossible in practically every thin section studied. Oddly enough, when not altered, the feldspar rarely shows distinct twinning; it is a faded, diffuse feature in these plagioclases. There is also considerable alteration of biotite to chlorite and/or epidote.

The microstructure of the Iterungnek gneisses is also grossly similar to that of the Uivak gneisses. However, quartz is much more irregular, generally not having the smooth elongate aspect of the Uivaks. Instead it has a very globular, ameboid form, and its invariable absorption contacts against other phases, especially plagioclase, and numerous inclusions of coexisting minerals indicate that it was mobile until the late stages of the final crystallization of these rocks. These and other features are described below.

The "streaky gneisses" which have been derived both by reconstitution of the earlier Uivak gneisses and syntectonic granitic stringers, and which still occasionally contain small enclaves of Uivak gneisses have the assemblage

Quartz-plagioclase-microcline-biotite.

Epidote, allanite, zircon, apatite, carbonate and chlorite are the chief accessories. With the exception of apatite, zircon, and allanite, the accessories are alteration products of other phases. A veinlet of prehnite was observed in one rock (152). The plagioclase to microcline ratio is variable, i.e., some rocks have much more microcline than plagioclase (up to 80:20) while others are vice versa.

Quartz in some of the streaky gneisses is extremely elongate, up to 1 × 0.2 cm, and displays the widest array of deformation features observed in the Iterungnek suite. In fact, some of the microstructures resemble those in cataclastic rocks. Undulose extinction, deformation bands and subgrain structures are ubiquitous. The original grains occasionally have developed smaller elongate new grains, along the boundaries of which occur zones of renewed polygonization. The grain interfaces of these new grains vary from straight to sutured, and commonly coalesce and migrate into the host grain (Plate 22a). This is developed to a much greater extent than in the Uivak gneisses. Where not polygonized, quartz grain boundaries are scalloped to lobate especially at quartz and microcline interfaces, though embayed against plagioclase. It contains inclusions of the other constituents. In other streaky gneisses the quartz shows less pronounced deformation substructures, occurring as undulose grains with poorly developed deformation domains and prominent deformation lamallae.

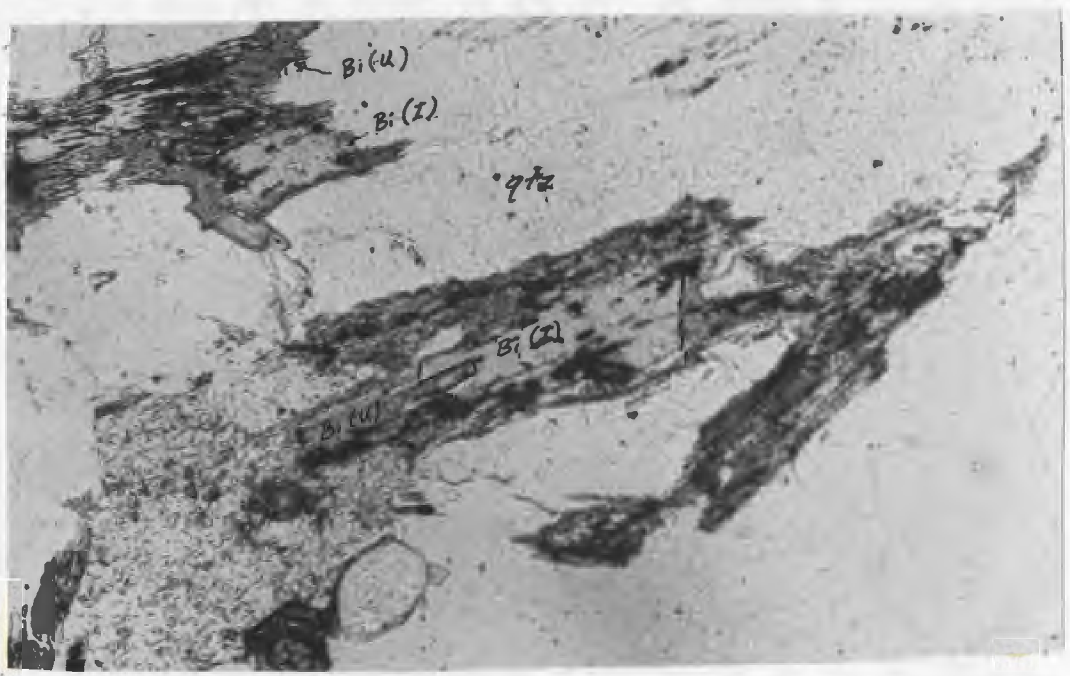
Plagioclase feldspar is generally smaller than the coexisting microcline, this being especially so when the potassium feldspar predominates. Plagioclase forms xenomorphic grains averaging 2 × 1 mm in size. It is extensively sericitized, with flakes of white mica throughout the grains; there is much less alteration on the margins of grains in contact with microcline. The borders of plagioclase grains in contact with microcline also have a narrow (0.05 mm) rim in slightly different optical orientation from the rest of the grain. There are also the sites of micro-myrmekite growth on the plagioclase. These features are interpreted to be indicative of a slightly different chemical composition for the margins of the plagioclase (more Ca-rich?), a feature caused by reaction with the adjacent K-feldspar. Muscovite present in these rocks is invariably associated with plagioclase, and mutual relations indicate that the mica is replacing the feldspar. The alteration of the feldspar is so extensively developed that accurate compositional determinations were not possible. From the thin sections studied, eight dubious compositions were obtained, ranging from An_{22} to An_{38}. Plagioclase grain boundaries are commonly embayed by quartz, otherwise curved interfaces predominate. Microcline/plagioclase contacts are commonly myrmekitic, with vermicular quartz penetrating the latter.

Microcline has a xenomorphic form (up to 5 mm in maximum dimension) with very irregular grain boundary contacts with other constituents; in contrast to the altered state of

PLATE 22

MICROSTRUCTURES OF ITERUNGNEK GNEISSES

22a. New grains generated at the margins of larger quartz grain in "streaky gneisses". (X 60)



22b. Iterungnek biotite overgrown an earlier Uivak biotite. The granular inclusions outline the earlier grain. (X 100) the plagioclase, it is fresh. It is commonly perthitic, with ribbon and flame being the two prevalent forms; grid-iron twinning is variably developed. Inclusions of biotite, plagioclase and quartz have been observed, but not common.

Biotite in the streaky gneisses is of two types, a sagenitic variety believed to be a relic from the Uivak gneisses and an inclusion-free one interpreted to be related to the formation of the streaky gneisses. The latter replaces the former. Biotite occurs either as bladed, subidiomorphic grains forming a weak compositional banding, or as stringy aggregates. Maximum grain size is 1×0.2 mm. Rutilized biotite is not common in the Iterungnek streaky gneisses. It appears to have recrystallized, expelling the rutile needles as granular clusters which have aggregated within the grains, commonly along cleavage traces, or as marginal rims. In some rocks (5) younger biotite, considered to be related to the refoliation of the Uivak gneisses, can be observed to replace the earlier sagenitic Uivak mica. It seems to be a progressive process, during which the younger biotite overgrows the older, the latter recrystallizes, and rutile is expelled becoming oriented along the older's cleavage traces. The younger biotite overgrows the inclusion trains, occasionally with its cleavage lines perpendicular to the direction of orientation of the inclusions which mimic the outline of the Uivak mica (Plate 22b). Pleochroism in the sagenitic Uivak biotite is X = buff, Y = Z = greenish brown, nearly opaque, and in the Iterungnek biotite varying from X = golden yellow to Y = Z = deep brown. Both biotites have been replaced by green, pleochroic chlorite and/or epidote (pistacite) in several of the streaky gneisses studied, and consequently its original type cannot always be established. Granular clusters within the chlorite may be expelled rutile from Uivak biotite, or it may be rutile formed by expulsion of titanium from the younger biotite, a common occurrence in the alteration of mica (Schwartz, 1959).

The modified Uivak "stringers" in the lit-par-lit migmatites at the entrance to Jerusalem Harbour (1a, 138) have the assemblage

Quartz-plagioclase-microcline-biotite
(± clinopyroxene).

Allanite, apatite, zircon and green shredded biotite are accessory constituents.

Quartz is ameboid, globular shaped, somewhat elongate, but lacks an overall lenticular aspect. It ranges in size from minute blebs to 5 × 4 mm. Grain contacts between it and other phases vary from curved to embayed to serrated. It shows evidence of strain in the form of undulatory extinction, deformation bands and subgrains; new grains developed from larger hosts are uncommon. Its large size and globular form enables it to enclose both feldspars, biotite and pyroxene.

The plagioclase to microcline ratio is again variable.

Plagioclase (An_{28-30}) has a xenomorphic form and reaches a maximum size of 2 × 1 mm. It exhibits undulose extinction; twins, when present, are commonly kinked, dying out when entering a kink-band. Generally twinning is absent, or very indistinct. There is some sericitization and alteration along margins and intragrain fractures to shredded green biotite. Grain contacts against other species are curved and scalloped, except against mica where the interfaces are straight. Ovoid inclusions of quartz and microcline are present.

Microcline, occurring as fresh xenomorphic grains with its characteristic complex cross-hatched twinning pattern, reaches a maximum size of 4 × 2 mm when it is the dominant feldspar. Flame and stringlet perthite are nearly always present in the K-feldspar. It contains inclusions of quartz, plagioclase and biotite, and again myrmekitic intergrowths are present at microcline/plagioclase boundaries, with quartz worms transgressing twin planes in the latter.

Two varieties of biotite are present. The fabric forming biotite is a pleochroic (X = buff, Y = Z = brown) variety without the sagenite which commonly typifies the Uivak gneisses. Several grains of sagenitic biotite were observed in thin sections, but are interpreted as relics since two of the grains were partially recrystallized, with the expulsion of the rutile needles as granular clusters. The foliation forming biotite occurs as bladed grains averaging

1.5 × 0.5 mm in size. The second biotite is the green shredded variety described from other rocks in this area. Its relationship to the other minerals indicates that it is a late product. It replaces all other species, either as marginal overgrowths or as branching arterial growths along fractures within grains. It also forms bright green coronal growths around subrounded matted aggregates of minute needles of green biotite and quartz. These latter matted forms appear to be a replacement of a colourless bladed amphibole, which had previously replaced pyroxene (see below).

Colourless to very pale green clinopyroxene occurs in one thin section (1a) of the foliated portion of the lit-par-lit migmatites. It forms xenomorphic relics up to 1.5 mm in diameter, surrounded by greenish actinolite, the same relationship described from the Fe-rich members of the Uivak suite. In addition, narrow rims of granular epidote occur around the amphibole. No hornblende has been found in the thin section in question, a mineral which is an essential constituent of the assemblage described earlier, and therefore it is difficult to say if this rock is part of the iron-rich Uivak II gneisses or not. Fine grained aggregates of bladed, colourless amphibole like that described from the Uivak gneisses is also present in this rock, and maybe pseudomorphs of orthopyroxene as stated earlier. However, as before, no relic grains remain, and this relationship is based on the presence of similar amphibole replacing orthopyroxene in "sweat" pegmatites (see below). The bladed amphibole is too fine grained to obtain enough optical properties for positive identification, but the following features were noted. The blades exhibit extinction parallel or nearly parallel to their length, and optic axis figures obtained on uniformly low birefringent aggregates indicate that the mineral is optically negative with a 2V angle of $\sim 80°$. It could possibly be cummingtonite (Deer, Howie and Zussman, 1971, p.160).

The nebulite zones with a whispy foliation into which the lit-par-lit migmatites fade along strike have the assemblage

Quartz-plagioclase-microcline-biotite.

The rocks are much coarser grained than the foliated banded gneisses, with quartz up to a centimeter in diameter. The microstructure is xenoblastic inequigranular in which grain relations are similar to those described from previous rocks, and will only be briefly treated here. There is no strong preferred orientation to the mineral constituents. Quartz has a globular, ameboid form, the grains showing undulatory extinction and subgrain development. Plagioclase, exhibiting either very diffuse twins or no twins at all, forms subidiomorphic grains up to 3 × 3 mm. It is altered to sericite and carbonate. Microcline, smaller than plagioclase, occurs as fresh, twinned grains between the other constituents. Flame and ribbon perthite are common. The biotite present is largely sagenitic, and interpreted to be Uivak in age. However there is replacement by inclusion-free biotite as described earlier, but the transformation of the old and the crystallization of the new biotite is not nearly as complete as in the foliated rocks. The nebulitic gneisses throughout the area have similar mineral assemblages. Grain size varies, and in some rocks Uivak biotite outlining "ghost-folds" has been nearly completely replaced by the inclusion-free Iterungnek biotite.

The diffuse pegmatites, which occur as local irregular patches, or linear transgressive lens, contain

Quartz-plagioclase-microcline,biotite-(retrogressed) orthopyroxene.

The felsic constituents display the same microstructural features as before, i.e. all constituents are xenomorphic inequigranular, up to 7 mm in diameter, with embayed, scalloped and curved interfaces, with quartz being a corroding agent. Plagioclase may contain antiperthitic patches of microcline. Brown biotite when present (71b) may be an inclusion-free type very similar pleochroically to that in the pelitic rocks, varying from X = buff or golden yellow to Y = Z = intense rusty red, or it may be sagenitic Uivak biotite. Rutile needles have been largely expelled along the cleavage planes; inclusion-free biotite growing within the cleavage traces of the Uivak biotite, has "forced apart" the older mica.

Orthopyroxene has been largely replaced by an association of various minerals. The pyroxene, pink to pale green pleochroic hypersthene, occurs as granular "islands", with a maximum size of 2 mm in diameter, surrounded by a pseudomorphic assemblage of fine-grained white mica (sericite), abundant opaque oxides, and a colourless amphibole (71b). It is also replaced by the colourless bladed amphibole (with few opaques) in which no relic pyroxene remains (116). In the first association mentioned above, the amphibole is poorly developed, and usually forms a serrated rim around the sericite-opaque oxide assemblage, and as radiating clusters nucleating perpendicular to linear aggregates of the opaques. There appears to be a reaction between the sericite and the opaque mineral to generate the bladed amphibole, which when complete, uses up any remaining orthopyroxene. It is probably significant therefore, that relic orthopyroxene occurs in the sericite-opaque oxide-amphibole assemblage and not in the bladed amphibole aggregates. The amphibole which forms much larger blades (up tp 0.4 x 0.2 mm) than in the previously described rocks shows very narrow polysynthetic twinning, another feature which is suggestive of cummingtonite (Deer, Howie and Zussman, 1971) as suggested by the other optical properties mentioned earlier. It has associated with it, in some rocks, a blue-green hornblende into which it grades imperceptibly; the hornblende usually occurs on the margin of the bladed amphibole.

The mineral associations which replace orthopyroxene are invariably surrounded by a radiating corona ($\sim$0.05 mm wide), or discrete flakes, of green biotite, which also penetrates along fractures in, and replaces, adjacent feldspar. The biotite rims are absent from quartz-altered pyroxene contacts.

The various microscopic features of the orthopyroxene transformation described above are shown in Plate 23.

The foliated granitic rocks which intrude, brecciate and extensively disrupt basic gneiss bodies on Morhardt Point and Mt. Jerusalem have the common assemblage

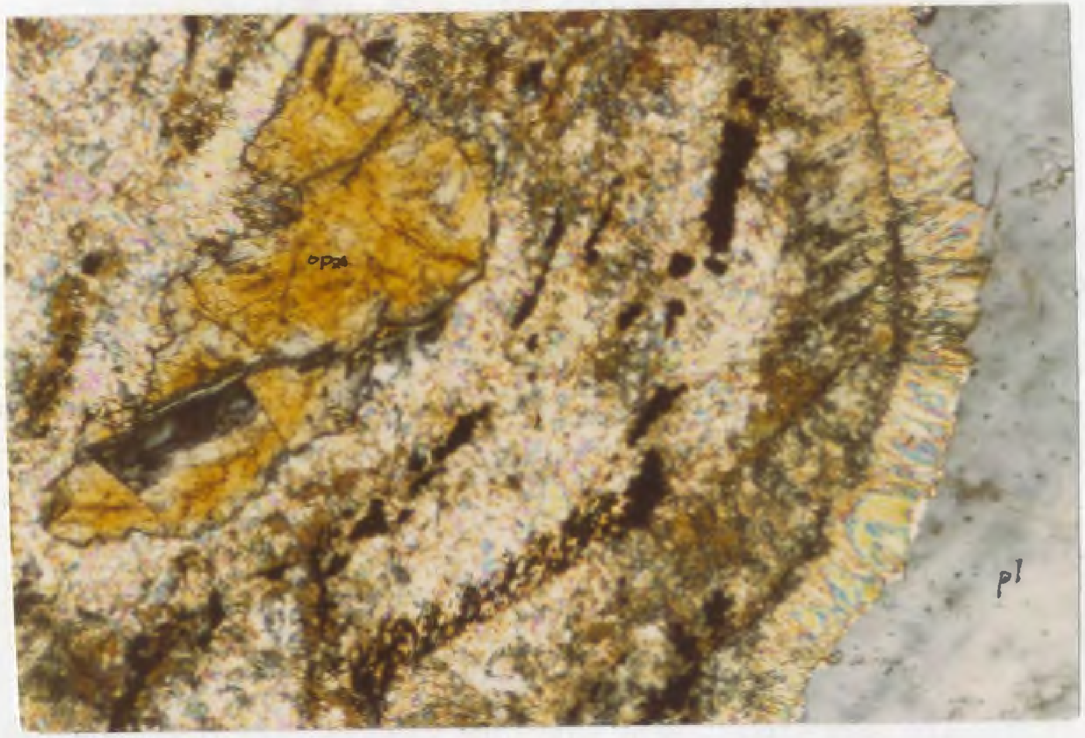
Quartz-plagioclase-microcline-biotite.

The Morhardt Point rock is chiefly a medium-grained granodiorite, that from Mt. Jerusalem being a coarser grained tonalite. Though grain size varies between the two rocks - the granodiorite containing grains mainly between 2 and 7 mm in maximum dimension, the tonalite containing grains between 5 mm and 1.5 cm in size -- the relationship between the major constituents is very similar.

There is no pronounced dimensional orientation of quartz in either rock. It forms weakly lenticular ameboid grains and aggregates, which in the tonalite reach over 2 cm in length. Strain shadows and subgrains are developed in the quartz of both rocks; new grains have formed at host grain margins.

PLATE 23

ORTHOPYROXENE ALTERATION



23. Orthopyroxene (core) surrounded by sericite(?)-opaque oxide-colourless amphibole assemblage, with a further corona of green biotite against plagioclase. (X 60)

The plagioclase feldspar forms xenomorphic grains with curved or embayed boundaries. Diffuse twinning may be present, but the degree of sericitization is too great to allow reliable compositional determinations. In the tonalite ragged, but descrete, flakes of muscovite have partially replaced the plagioclase.

Microcline is an essential constituent of the Morhardt Point granodiorite, but is only an accessory phase in the tonalite from Mt. Jerusalem. It occurs as xenomorphic, fresh, twinned grains containing inclusions of the other phases. There is a noticable absence of myrmekite at microcline/plagioclase interfaces in these rocks; both feldspars form sharp boundaries with each other.

Biotite occurs in both rocks. It is a sagenitic variety in the tonalite, but only occurs in accessory amounts. In the granodiorite there are no rutile needles in the biotite, but it is full of "strings" of granular inclusions, and overgrowths similar to those described for the transformation and recrystallization of Uivak biotite have been observed. In the granodiorite, biotite is replaced by green chlorite and epidote.

A xenomorphic, granular garnet, 3 mm in diameter, largely replaced by chlorite, was observed in a thin section of the Morhardt Point granodiorite. Its presence in such a rock is enigmatic because garnets have not been observed in any of the quartzofeldspathic gneisses of similar composition. Whether it is a mineral crystallized from the original granitic melt, a xenocryst from assimilated garnet-bearing gneisses, or a metamorphic mineral synchronous with the reworking of the Uivak gneisses is difficult to say.

CHAPTER IV

METAMORPHISM

IV.1. Introduction.

The interpretation of the metamorphic evolution of polymigmatitic gneiss terrains is a difficult task, since relics of the early metamorphic history of such rocks may be preserved at one locality, yet obliterated in an adjacent area (cf. Mehnert, 1968). Such is the case with the Archean gneisses from Labrador whose field and petrological characterisitcs have been described in the previous chapter (see also Bridgwater et al.,1975, Collerson, et al., 1976).

Some aspects of the metamorphic history of these rocks will be described below in the light of the petrographic features described previously. Many of the problems involved with the evolution of these rocks have yet to be solved, pending future work in the region.

There are many indications that the gneisses of the study-area and those at Saglek have had a long history of metamorphic mineral growth. For instance, there is evidence for a metamorphism affecting the pre-Uivak inclusions, at least two migmatitic/metamorphic periods in the Uivak gneisses themselves, and a metamorphism accompanying the later reconstitution of the Uivak gneisses and the formation of the Iterungnek gneisses. The intensity of each later metamorphic overprinting has dictated whether early assemblages remain or have been completely destroyed by renewed recrystallization. The latter metamorphism mentioned above is the one of main concern to this thesis.

The petrographic evidence from microstructures and mineral assemblages in the rocks around Jerusalem Harbour indicate that these rocks do not exhibit features consistent with a high degree of microstructural equilibrium, e.g. preponderence of curved and embayed grain boundaries instead of well-defined polygonal aggregates with 120° triple point junctions; the co-existence of minerals which are apparently metastable, such as hornblende and orthopyroxene; and the frequent occurrence of lower grade pseudomorphs of earlier metamorphic minerals and coronal growths around several phases. In order to understand the metamorphic evolution of these rocks it is necessary to decide which petrographic features are indicative of prograde or retrograde mineral reactions, and therefore postulate on assemblages which indicate specific metamorphic conditions. The discussion below deals with some of the petrographic features previously described from each of the major rock groups, and interprets them in terms of metamorphic mineral reactions which could have occurred in the rocks. The final section gives a tentative petrogenetic grid for the physical conditions during the development of the mineral assemblages seen in the gneisses.

IV. 2 The Uivak Gneisses and their Inclusions.

The largest continuous outcrops of unreworked Uivak gneisses occur on the south side of Iterungnek Fiord, where they contain rafts of pre-Uivak lithologies and Saglek dykes. These and other outcrops in the area which have undergone negligible visible mesoscopic reconstitution are considered to contain mineral assemblages which were imprinted on them by a metamorphic event 3.6 B.Y. ago. The mineralogy of such rocks is consistent with that which would be expected within the upper amphibolite facies of regional metamorphism (Turner, 1968), e.g. hornblende and biotite are the chief ferromagnesian constituents. There is no evidence of any anhydrous mafic minerals within any unreworked Uivak gneisses studied.

Similarly, the mineralogy of the few pre-Uivak inclusions and Saglek dykes examined is consistent with these metamorphic conditions.

Therefore it may be concluded that the mineral assemblages seen in the unreworked Uivak gneisses in the region are those which developed at 3.6 B.Y. ago and are identical with assemblages found east of the Handy Fault at Saglek (Bridgwater and Collerson, 1976); no detectable radical changes in mineralogy have occurred since that time.

It was mentioned at the onset of the description of the Uivak gneisses in the previous chapter (p.39) that the account also included those gneisses which were slightly reconstituted but still retained the field characteristics of the Uivak suite. It is in these rocks that a picture of new mineral growth emerges.

Although clinopyroxene has been found in unreworked dioritic Uivak gneisses at Saglek, no pyroxenes were found in Uivak gneisses in the present area except in zones where they can be demonstrated to have been reworked. In such rocks in the study-area it is most prominent as an axial planar growth to folds in reworked Fe-rich Uivak II gneisses. In these rocks it has formed at the expense of a green-brown hornblende, with minor orthopyroxene (now a colourless bladed amphibole) also being formed in the process. The reaction which represents the instability of hornblende and quartz under prograde metamorphic conditions is given by Ramberg (1948) and de Waard (1965) as

$$\underset{\text{Hornblende}}{NaCa_2(Mg,Fe)_4Al_3Si_6)O_{22}(OH)_2} + \underset{\text{Quartz}}{4SiO_2} \longrightarrow \underset{\text{Plagioclase}}{NaCaAl_3Si_5O_{16}} +$$

$$\underset{\text{Clinopyroxene}}{Ca(Mg,Fe)Si_2O_6} + \underset{\text{Hypersthene}}{3(Mg,Fe)SiO_3} + \underset{\text{Water}}{H_2O}$$

and is considered to be a viable reaction in the hornblende-bearing Uivak II gneisses in light of the petrographic features observed.

Both the pyroxenes and the hornblende have suffered a later transformation to lower grade minerals. The clinopyroxene and the hornblende have been replaced by pale-green actinolite, the clinopyroxene moreso than the hornblende; the orthopyroxene has been replaced by a fine matted growth of bladed colourless cummingtonite.

The clinopyroxene alteration may be envisaged simply as

$$\underset{\text{Clinopyroxene}}{5Ca(Mg,Fe)Si_2O_6} + \underset{\text{Water}}{H_2O} + \underset{\text{Carbon Dioxide}}{3CO_2} \longrightarrow \underset{\text{Actinolite}}{Ca_2(Mg,Fe)_5Si_8O_{22}} + \underset{\text{Quartz}}{2SiO_2}$$

(Hashimoto, 1972). However, it is probable that the clinopyroxene in the Fe-rich Uivak II suite is hedenbergitic rather than diopsidic, and therefore a more accurate reaction may be

$$\underset{\text{Hedenbergite}}{5CaFeSi_2O_6} + \underset{\text{Carbon Dioxide}}{3CO_2} + \underset{\text{Water}}{H_2O} \longrightarrow \underset{\text{Ferroactinolite}}{Ca_2Fe_5Si_8O_{22}(OH)_2} + \underset{\text{Calcite}}{3CaCO_3} + \underset{\text{Quartz}}{2SiO_2}$$

(Deer, Howie, and Zussman, 1963). Where plagioclase has been altered to epidote minerals the reaction may be envisoned as being of the type:

$$5Ca(Fe,Mg)Si_2O_6 + 9CaAl_2Si_2O_8 + 4H_2O \longrightarrow 6Ca_2Al_3Si_3O_{12}(OH) +$$

Clinopyroxene Plagioclase Water Epidote

$$Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2 + 2SiO_2$$

Actinolite Quartz

(Cliff, Norris, Oxburgh and Wright, 1971).

In the Saglek dykes the actinolite which formed by the replacement of clinopyroxene displays coronas of granular and acicular epidote adjacent to plagioclase. The reaction

$$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2 + 10CaAl_2Si_2O_8 + 6H_2O \longrightarrow$$

Actinolite Plagioclase Water

$$6Ca_2Al_3Si_3O_{12}(OH) + (Mg,Fe)_5Al_2Si_3O_{10}(OH)_8 + SiO_2$$

Epidote Chlorite Quartz

(Strens, 1965) may be used to explain this feature. The combination of these two reactions indicates that epidote of two ages exists in the Saglek dykes.

The replacement of hornblende by actinolite may be a variant of a reaction proposed by Shido (1958) namely

$$25Ca_2(Fe,Mg)_3Al_4Si_6O_{22}(OH)_2 + 44H_2O \longrightarrow Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$$

Hornblende Water Actinolite

$$+ 14\ Mg_5Al_2Si_3O_{10}(OH)_8 + 24Ca_2Al_3Si_3O_{12}(OH) + 28SiO_2$$

Chlorite Epidote Quartz

No orthopyroxene remains in the slightly reconstituted Uivak gneisses. Its former presence is inferred from the habit of a colourless amphibole identical to that observed replacing orthopyroxene in diffuse pegmatites in the Iterungnek nebulites. The reaction

$$7(Mg,Fe)SiO_3 + H_2O + SiO_2 \longrightarrow (Mg,Fe)_7Si_8O_{22}(OH)_2$$

Hypersthene Water Quartz Cummingtonite

(Stewart, 1947) seems to be applicable to the observed petrographic relationship.

A second hornblende, a blue-green variety, is also present in the slightly reconstituted Uivak gneisses, generally in irregular leucocratic blotches interpreted as zones of partial melting (cf. Busch, 1966). These hornblende-bearing areas are impoverished in brown biotite relative to the rest of the rock. A reaction described by Busch (1966) and Wooden et al.,(1975), and investigated experimentally by Mehnert et al.,(1973), can be used to explain this feature, viz. Biotite + Plagioclase (An_{45}) + Quartz $\longrightarrow$ Hornblende + K-feldspar + Plagioclase (An_{35}) + Sphene + Water. The relatively small size of the blotchy melt zones in the Uivak gneisses of this area indicate that this reaction is only of limited extent in these rocks. More extensive blotchy zones in rocks which may be considered "diatexites" in the Saglek area contain garnet instead of hornblende. Gilbert (1966) and Cawthorn and Brown (1976) have noted that the crystallization of hornblende or garnet is dependent on the oxygen fugacity and partial pressure of water, garnet being favoured under higher P_{H_2O} and lower fo_2 than hornblende. These parameters may have governed the paragenesis observed in the present area compared to Saglek.

The hornblende in these blotchy zones has been replaced by a stellate green biotite-quartz ± opaque oxide assemblage, the mica and quartz commonly exhibiting a symplectic intergrowth. This may be due to a reversal of the above reaction, or possibly an equation of the type

$$\underset{\text{Hornblende}}{Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2} + \underset{\text{dissolved potash silicate}}{K_2O + SiO_2 + H_2O} \longrightarrow$$

$$\underset{\text{Biotite}}{K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + \underset{\text{Epidote}}{Ca_2Al_3Si_3O_{12}(OH)} + \underset{\text{Quartz}}{SiO_2}$$

(Ramberg, 1952). However there is no evidence that epidote was a product in the biotite-quartz replacement of the hornblende, and therefore this may not be a valid expression for the observed relationship.

IV. 3 The Upernavik Supracrustals.

The metasedimentary rocks are almost totally devoid of any microstructural features which may be used to establish specific reactions by which a particular mineral species was generated. The present assemblages in the metasediments are considered to be a result of metamorphism accompanying the reconstitution of the surrounding gneisses. Unfortunately there are no definite indicators of the earlier mineralogy.

However analagous rocks from the Upernavik supracrustals in unreworked Uivak gneisses at Saglek, with similar overall mineralogies, contain fibrolite instead of coarse sillimanite, but in reworked gneisses there, prismatic sillimanite is widely developed, just as in the metasediments of the study-area.

Biotite, the most common ferromagnesian phase in the rocks, may have formed through any one of a number of reactions from lower grade rocks. However, since it also occurs in the unreworked equivalents of these rocks, the present biotite may simply be a compositional variant recrystallized from the earlier rocks.

Sillimanite, the other foliation forming species may have developed as a result of the coarsening and nucleation of earlier fibrolite, or it may have formed by reactions such as:

$$\underset{\text{Staurolite}}{6(Fe,Mg)_2(Al,Fe)_9O_6(SiO_4)_4(OH)_2} + \underset{\text{Muscovite}}{4KAl_3Si_3O_{10}(OH)_2} + \underset{\text{Quartz}}{7SiO_2}$$

$$\longrightarrow \underset{\text{Sillimanite}}{31Al_2SiO_5} + \underset{\text{Biotite}}{4K(Mg,Fe)_3AlSi_3O_{10}(OH)_2} + \underset{\text{Water}}{3H_2O}$$

(Billings, 1937)

or

$$\underset{\text{Almandine}}{Fe_3Al_2Si_3O_{12}} + \underset{\text{Muscovite}}{4KAl_3Si_3O_{10}(OH)_2} \longrightarrow \underset{\text{Sillimanite}}{2Al_2SiO_5} +$$

$$K(Mg,Fe)_3AlSi_3O_{10} + SiO_2$$
Biotite Quartz

(Thompson and Norton, 1968).

The absence of the quartz + muscovite assemblage and the presence of (relatively rare) microcline implies that conditions of the "second sillimanite isograd" were attained, and the reaction

$$(K,Na)Al_3Si_3O_{10}(OH)_2 + (Na,Ca)Al_2Si_2O_8 + SiO_2 \longrightarrow Al_2SiO_5 + (K,Na)AlSi_3O_8 + (Ca,Na)Al_2Si_2O_8 + H_2O$$
Muscovite, Sodic plagioclase, Quartz, Sillimanite, K-feldspar, Calcic plagioclase, Water

(Guidotti, 1963) occurred.

The muscovite pseudomorphs after sillimanite may be due to a reversal of the above reaction under decreasing metamorphic conditions, or it may be due to

$$3Al_2SiO_5 + K_2O + 3SiO_2 + H_2O \longrightarrow 2KAl_3Si_3O_{10}(OH)_2$$
Sillimanite Muscovite

(Deer, Howie and Zussman, 1963).

Kwack (1971) has pointed out the possible significance of ionic transformations of the aluminosilicates through the reaction

$$3Al_2SiO_5 + 3SiO_2 + 3H_2O + 2K^+ \longrightarrow 2KAl_3Si_3O_{10}(OH)_2 + 2H^+$$
Sillimanite Muscovite

It was noted earlier that prismatic sillimanite occurs within completely pinitized cordierite, yet the alumino-silicate is unaltered. In the cordierite-free rocks however, sillimanite is extensively transformed to muscovite. This situation may be analogous to Kwack's investigations of the aluminosilicates in that due to high a_{K^+} the cordierite was selectively replaced in the sillimanite-cordierite bearing rocks, but sillimanite readily transformed in cordierite-free rocks. Sillimanite was not altered when cordierite existed because the migrating fluids were buffered with respect to K^+ and H^+ near the lowest stability field of cordierite. Once cordierite was destroyed (or if not originally present) the fluid composition changed so that it entered the stability field of sillimanite, and it (the sillimanite) then similarly retrogressed to white mica. The H^+ liberated by the above reaction may also be the chief contributing factor in the replacement of biotite by muscovite as described for the pelitic rock from Hebron (p.66)(cf. Gresens and Strensrud, 1974, p.1587).

Garnet and cordierite overgrow the foliation, and in some examples are slightly elongate within this fabric. The impression gleaned from the thin sections is that these two minerals formed during the waning stages of deformation. The actual reaction by which these two phase formed is not clear, but a reaction of the type

$10K_2(Fe,Mg)_5Al_3Si_5O_{20}(OH)_4 + 28Al_2SiO_5 + 65SiO_2$

Biotite Sillimanite Quartz

$\longrightarrow 11(Mg,Fe)_2Al_4Si_5)_{18} + 11(Mg,Fe)_3Al_2Si_3O_{12} +$

Cordierite Garnet

$20KAlSi_3O_8 + 20H_2O$

K-feldspar Water

(de Waard, 1965a)

or

$K(Fe^{\bullet},Mg)_3AlSi_3O_{10}(OH)_2 + Al_2SiO_5 \longrightarrow (Fe,Mg)_3Al_2Si_3O_{12}$

Biotite Sillimanite Garnet

$+ KAlSi_3O_8 + H_2O$

K-feldspar Water

(Rivalenti and Rossi, 1972, p.62) may have been active. The latter reaction may also account for the smaller size of the sillimanite forming the internal fabric in the garnets.

The retrogression of the garnet may be due to the influx of water leading to

$3(Fe,Mg)_3Al_2Si_3O_{12} + 8H_2O \longrightarrow (Fe,Mg)_5Al_2Si_3O_{10}(OH)_8 +$

Garnet Water Chlorite

$4SiO_2$

Quartz

(Hsu, 1968).

The pinitization of the cordierite can be explained as

$$\underset{\text{Cordierite}}{(Fe,Mg)_2Al_4Si_5O_{18}} + \underset{\text{Biotite}}{K(Fe,Mg)_3AlSi_3O_{10}(OH)_2} + \underset{\text{Water}}{4H_2O} \longrightarrow$$

$$\underset{\text{Chlorite}}{(Fe,Mg)_5Al_2Si_3O_{10}(OH)_8} + \underset{\text{Muscovite}}{KAl_3Si_3O_{10}(OH)_2} + \underset{\text{Quartz}}{2SiO_2}$$

(Turner, 1968).

Since only a few of the impure calc-silicate rocks have been examined, their paragenesis cannot be considered in detail. However the presence of relic muscovite within the zoisite and the abundance of microcline indicate a prograde metamorphic reaction of the type

$$\underset{\text{Muscovite}}{3KAl_3Si_3O_{10}(OH)_2} + \underset{\text{Calcite}}{4CaCO_3} + \underset{\text{Quartz}}{6SiO_2} \longrightarrow \underset{\text{Zoisite}}{2Ca_2Al_3Si_3O_{12}(OH)}$$

$$+ \underset{\text{Microcline}}{3KAlSi_3O_8} + 4CO_2 + 2H_2O$$

(Thompson, 1975). The amphibole which rims the diopside is considered a retrograde feature, a result of

$$\underset{\text{Diopside}}{5CaMgSi_2O_6} + 3CO_2 + H_2O \longrightarrow \underset{\text{Tremolite}}{Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\text{Calcite}}{3CaCO_3}$$

$$+ \underset{\text{Quartz}}{2SiO_2}$$

(cf. Hewitt, 1973, p.455).

The basic gneiss units of the Upernavik supracrustals give a good indication of the maximum grade of metamorphism attained in the area. The mineralogy of these rocks is also considered to be largely a result of recrystallization during the reconstitution of the gneisses with which they are interbanded. The presence of orthopyroxene in the basic rocks is a definite indicator that granulite facies conditions prevailed during the recrystallization of these rocks (Turner, 1968; Winkler, 1974). The brown pleochroism of the hornblende is also diagnostic of metabasic rocks in granulite facies (Binns, 1964; Engel and Engel, 1962; Engel, Engel and Havens, 1964). Microstructural evidence bearing on the sequence of recrystallization of hornblende and pyroxenes is sometimes rather ambiguous, but it appears that orthopyroxene and clinopyroxene have been generated at the expense of hornblende through a reaction of the type presented earlier, i.e.

$$\underset{\text{Hornblende}}{NaCa_2(Mg,Fe)_4Al_3Si_6)_{22}(OH)_2} + \underset{\text{Quartz}}{4SiO_2} \longrightarrow \underset{\text{Plagioclase}}{NaCaAl_3Si_5O_{16}}$$

$$+ \underset{\text{Clinopyroxene}}{Ca(Fe,Mg)Si_2O_6} + \underset{\text{Orthopyroxene}}{3(Mg,Fe)SiO_3} + H_2O$$

The plagioclase rims developed around garnet, described from the basic rock from Jerusalem Harbour, are believed to be a result of the instability of garnet and hornblende under prograde metamorphic conditions, such that

$$NaCa_2(Fe,Mg)_4Al_3Si_6O_{22}(OH)_2 + (Fe,Mg)_3Al_2Si_3O_{12} + 5SiO_2$$

Hornblende Almandine Quartz

$$\longrightarrow 7(Fe,Mg)SiO_3 + NaCa_2Al_5Si_7O_{24} + H_2O$$

Orthopyroxene Plagioclase Water

(de Waard, 1965b) occurred. An identical situation to that described from the rocks of the present area is shown by de Waard (op.cit.,Fig.4), who considers that this reaction indicates progressive metamorphism from upper amphibolite to granulite facies conditions (see also Clark, 1970, p.294). Prograde metamorphic conditions are also indicated by the reverse zoning in the plagioclase feldspars of some of the basic rocks (cf. Cannon, 1966; Rambaldi, 1973).

IV. 4. The Iterungnek Gneisses.

The Iterungnek gneisses, because of their dominantly "granitic" character, have very little to offer in the way of mineral assemblages which would indicate metamorphic conditions in the area at the time of their formation. It is well known that rocks of granitic composition are not particularly sensitive to regional metamorphism, in the sense that they do not have assemblages which will recrystallize and yield new phases. The best evidence for metamorphic conditions during the formation of the Iterungnek gneisses is offered by the presence of orthopyroxene in sweat pegmatites in areas of nebulitic gneisses. The Iterungnek gneisses do however, present the best indications of retrogressive metamorphism.

The widespread development of sericite and epidote at the expense of plagioclase may be modelled by the two reactions below:

$$4CaAl_2Si_3O_8 + KAlSi_3O_8 + H_2O \longrightarrow 2Ca_2Al_3Si_3O_{12}(OH)$$

Plagioclase Microcline Water Epidote

$$+ KAl_3Si_3O_{10}(OH)_2 + 2SiO_2$$

Sericite Quartz

(Marmo, 1967)

$$3CaAl_2Si_3O_8 + Ca(OH)_2 \longrightarrow 2Ca_2Al_3Si_3O_{12}(OH)$$

Plagioclase Epidote

(Deer, Howie and Zussman, 1963).

The retrogression of orthopyroxene in the pegmatites has been presented earlier (p.   ) as

$$7(Mg,Fe)SiO_3 + H_2O + SiO_2 \longrightarrow (Mg,Fe)_7(Si_8O_{22}(OH)_2.$$

Hypersthene Water Quartz Cummingtonite

The overgrowth of green hornblende on cummingtonite in these pegmatites appears to be a continuation of the ortho-pyroxene $\longrightarrow$ cummingtonite $\longrightarrow$ hornblende reaction series (Deer, <u>et al</u>, 1963) and is represented by

$$3(Mg,Fe)_7Si_8O_{22}(OH)_2 + 14CaAlSi_2O_8 + 4H_2O \longrightarrow$$

Cummingtonite Plagioclase

$$7Ca_2(Mg,Fe)_3Al_4Si_6O_{22}(OH)_2 + 10SiO_2\ .$$

Hornblende Quartz

PLATE 27

TRANSPOSITION OF UIVAK BANDING, JERUSALEM HARBOUR

27a. Closely spaces parallel shear zones along which Uivak banding has been reoriented and/or attentuated.

27b. New banding produced by the mechanism above, with small enclave of original Uivak banding.

in the biotite-cordierite-almandine subfacies of the hornblende-granulite facies (de Waard, 1965a).

It is obvious from the previous discussions that the original high grade assemblage has suffered retrogressive metamorphism. However since all indications are that the granulite facies metamorphism accompanied the reconstitution of the Uivak gneisses, the writer has attempted to construct a tentative petrogenetic grid which represents PT conditions at this time. A discussion of a possible evolutionary sequence for the recrystallization of the rocks in the area, and other relevant factors pertaining to the metamorphism are presented after consideration of the grid.

The metasedimentary rocks provide data for the establishment of the necessary reactions which define the PT limits of metamorphism (Figure 9):

(i) The presence of sillimanite in metapelites indicate that the pressures and temperatures were within the sillimanite field of the aluminosilicate polymorph stability diagram. The diagram employed for the construction of Figure 9 is that of Richardson, Gilbert and Bell (1968).

(ii) The absence of prograde muscovite in the metasediments indicates that temperatures were above the "second sillimanite isograd". Thus conditions of metamorphism were to the right of the muscovite breakdown curve as given by Storre and Karotke (1971). This curve in conjunction with the aluminosilicate diagram indicates temperatures in the vicinity

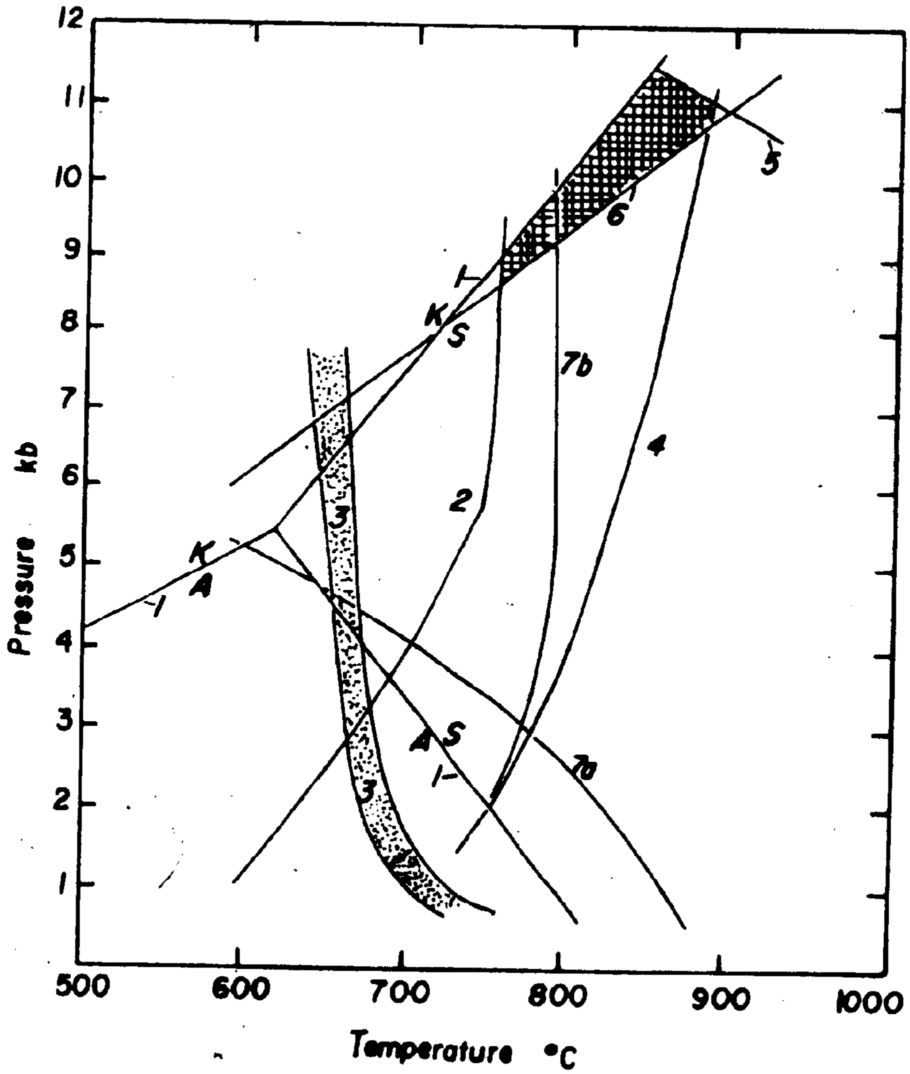


Figure 9. Petrogenetic grid with reaction curves relevant to metamorphism in the area (Cross-hatched). See text for discussion.

1. Aluminosilicate stability fields (Richardson et al., 1968)
2. Muscovite breakdown (Storre and Karokte, 1971)
3. Anatexis of quartzofeldspathic gneisses (Winkler, 1970)
4. Biotite breakdown in the presence of quartz (Currie, 1971)
5. Upper stability limit of cordierite (Hensen and Green, 1973)
6. First appearance of garnet in basic rocks of quartz tholeiite composition (Green and Ringwood, 1967)

7a. Hornblende breakdown at $P_{H_2O} = 1$ kb (de Wit and Strong, 1975)
7b. Hornblende breakdown at $P_{H_2O} = P_T$ (Binns, 1969).

of 700°C.

(iii) When the field of anatexis of quartzofeldspathic gneisses (Winkler, 1970) is plotted on the diagram it falls slightly below the PT conditions at the intersection of the muscovite breakdown curve with the aluminosilicate diagram. This is in agreement with the field relations which clearly indicate that anatectic conditions were attained in the area. The initial melting of the Uivak gneisses, as indicated by the small blotchy zones, could have begun at PT values as low as 2.8kb and 670°C.

(iv) The coexistance of quartz and biotite in the metasediments indicates that extreme temperatures of metamorphism were not realized in these rocks. The maximum temperatures are therefore bracketed by the breakdown of biotite (Currie, 1971), which indicates values in the vicinity of 900°C. It is possible that the orthopyroxene - bearing diffuse pegmatites in the Iterungnek nebulites resulted from the breakdown of biotite, and thus in such areas the upper temperatures were above those outlined by this curve.

(v) The presence of cordierite and garnet may be used to give an estimate of maximum and minimum pressures. There is no indication that the cordierite-bearing rocks ever attained conditions where the cordierite broke down to the high pressure assemblage sillimanite-quartz-hypersthene (Hensen and Green, 1973). Therefore maximum pressures were not above 11.5kb as defined by the intersection of the cordierite breakdown curve with the kyanite-sillimanite curve.

(vi) Although the reaction between garnet and hornblende to produce plagioclase and pyroxenes may be useful as a PT marker, no experimental data for this reaction is known to the writer. However a curve given by Green and Ringwood (1967) for the initial formation of garnet in the metagabbro has been utilized to give a minimum pressure for the area. The curve presented in Figure 9 is for rocks with $100\ Mg/(Mg,Fe^{2+}) \sim 55$.

(vii) The development of orthopyroxene in the basic rocks is believed to be due to hornblende breakdown, and heralds the beginning of granulite facies metamorphism, probably under conditions of varying P_{H_2O} (see below). Although no estimates of P_{H_2O} are possible from the present study, a curve for the breakdown of hornblende with $P_{H_2O} = 1$ Kb has been plotted in Figure 9 as given by de Wit and Strong (1975). Also given is a curve for hornblende breakdown with $P_{H_2O} = P_T$ as determined by Binns (1969).

The field of metamorphic conditions for the area as bounded by the prograde mineral-reaction curves used is rather restricted, as shown by the shaded area in Figure 9. The minimum temperatures are on the order of 750°C, and the maximum probably not above 900°C. The actual values are considered to be in the range of 825-850°C. Pressure estimates are bracketed between a low of 8.5 and a high of 11.5 kilobars. An intermediate value of 10 kb is considered a reasonable estimate for the area. It is interesting to note that these values are in good agreement with estimates determined from thermodynamic data for a late Archean granulite facies metamorphic event in southwest Greenland (Wells, 1976).

IV. 6. Brief Discussion of Petrogenesis.

The mineral reactions discussed in the first sections of this chapter are indicative of both prograde and retrograde metamorphism. Reactions of the prograde type indicate that the refoliation and recrystallization of the Uivak gneisses were accompanied by hornblende-granulite facies metamorphism, superimposed on rocks which previously exhibited mineral assemblages of the almandine-amphibolite facies. The sporadic distribution of mineral assemblages of both facies, as seen in the basic rocks, has made the demarcation of specific isograds impossible. The juxtaposition of assemblages of two metamorphic facies (cf. Cooray, 1972) even in different bands in hand specimens of the basic rocks, suggest that variations in PT conditions does not provide an adequate explanation for the pattern of mineral growth. An attractive alternative is to postulate localized variations in P_{H_2O} during metamorphism (cf. de Waard, 1964). The following evolution for the area is envisioned.

An original amphibolite facies terrain was subjected to crustal processes which caused remetamorphism of most of the rocks. The field of anatexis was breached, and conditions transitional into the granulite facies were attained at this time. The Uivak gneisses underwent varying degrees of partial melting and transposition. In the mildly deformed areas hornblende was produced at the expense of biotite in zones of initial melting, orthopyroxene and clinopyroxene were produced by the breakdown of hornblende in the presence of quartz in the transposed Fe-rich Uivak II gneisses. In zones of extreme melting, the Uivak gneisses were transformed into nebulites in which orthopyroxene-bearing diffuse pegmatites developed. Sillimanite and biotite were formed in the metasedimentary gneisses. In the basic rocks, dehydration reactions producing orthopyroxene at the expense of hornblende were initiated, and amphibolite facies garnet became unstable, giving rise to plagioclase and orthopyroxene. The dehydration reactions resulted in the expulsion of volatiles from the basic gneisses into the quartzofeldspathic gneisses surrounding them. Anatexis became more widespread, probably occurring at lower temperatures because of the relatively higher water fugacity (Dahl, 1971, p.11-12). This may explain the occurrence of granite sheets, many of which are concentrated within and adjacent to the basic gneisses.

During the transition into the granulite facies, deformation began to subside, but temperatures remained fairly constant. It was during these waning stages of deformation that cordierite and garnet developed in the metasediments, possibly at the expense of the sillimanite-biotite fabric which they overgrow.

The increasing P_{H_2O} in the leucocratic gneisses as a result of the hornblende breakdown in the basic rocks led to the post-tectonic retrogression (at slowly decreasing temperatures) of some of the previously existing minerals. These include the replacement of the pyroxenes by actinolite and cummingtonite, the breakdown of hornblende in the blotchy melt zones to a stellate green biotite-quartz symplectite, the pinitization of the cordierite and the muscovitization of sillimanite.

The development of epidote and sericite from plagioclase, the chloritization of biotite and garnet, and the growth of the "shredded" biotite are all considered to be much later low temperature transformations.

CHAPTER V

DEVELOPMENT OF THE ITERUNGNEK GNEISSES

V.1. Continental Crust: Addition of Mantle Material versus Reworking.

A divergence of opinions has recently arisen over the mechanism by which the continental crust of the Earth has grown through geological time. Has there been continual additions of juvenile material from the mantle, or has much of the younger crust formed by reworking of very early sial? This has been debated with respect to the formation of the granitic suite which was the precursor to the Nûk gneiss in Greenland. Some workers (e.g. McGregor, 1973; Pankhurst, Moorbath and McGregor, 1973; Moorbath and Pankhurst, 1976) consider the Nûk gneisses to represent calc-alkaline magmas emplaced into the crust from an upper mantle source region circa 3 billion years ago. Others (e.g. Chadwick and Coe, 1973; Chadwick, Coe, Gibbs, Sharpe and Wells, 1974a, 1974b, Bridgwater and Myers in Bridgwater et al., 1974) consider that the Nûk event involved a substantial amount of reworking of earlier sialic crust (the Amitsoq gneisses), synchronous with the injection of mantle-derived material.

This portion of the thesis represents a contribution to the controversy outlined above. It will be shown that the development of the Iterungnek gneisses in Labrador did indeed involve the reworking of an older gneiss suite, the Uivak gneisses. This has already been pointed out in field and isotopic studies at Saglek (Bridgwater et al., 1975; Collerson et al., 1976a; Hurst et al., 1975). The full extent of this type of tectonic activity in the Archean of Labrador has yet to be determined.

V.2. The Transformation of Uivak Gneisses to Iterungnek Gneisses - where to draw the line.

The transition from Uivak gneisses to the Iterungnek gneisses can be demonstrated at several localities in the region around Hebron Fiord and Jerusalem Harbour. The transformation is achieved by two principal mechanism, namely (i) a structural/ metamorphic reconstitution and (ii) a metamorphic/anatectic reconstitution. There are localities where each acted independently. and also where the two complement each other. In these zones of reworking it is difficult to pinpoint where Uivak gneisses, with abundant Saglek dykes, become Iterungnek gneisses, because recognizable pods of Saglek dyke can occasionally be found in the Iterungnek gneisses, though largely transformed to hornblendite.

In zones where the earlier gneisses are destroyed by a process of structural refoliation, the term Iterungnek gneiss is applied when the superimposed gneissosity becomes dominant over the original Uivak foliation, although the "new" gneiss at such localities may still possess features of the older rock, e.g. small enclaves, Saglek dyke pods. In areas where the

Uivak layering is obliterated by widespread partial melting and recrystallization, the name is applied to the nebulites which result, and also to the lit-par-lit gneisses bordering such zones which can be demonstrated to be migmatized Uivak gneiss.

The term Iterungnek gneisses is also applied to the foliated tonalitic and granodioritic rocks which are intrusive into the Uivak gneisses and Upernavik supracrustals. No Saglek dykes have ever been observed in these younger intrusions which are considered to be contemporaneous with the refoliation of the Uivak gneisses.

V.3. Examples of the Reworking of Uivak Gneisses.

The reworking of the Uivak gneisses and the syntectonic development of the Iterungnek gneisses is demonstrable at several localities within the study-area. An example of structural modification and of partial melting of the Uivak gneisses is described below.

(i) The areas which best display a structural modification of the Uivak gneisses are small coves on the west side of Cape Nuvotannak (58°12'40"N; 62°36'40"W) and on the north shore of Jerusalem Harbour (58°13'35"N; 62°38'10"W). The obliteration of Uivak structures and their replacement by an Iterungnek foliation is easily demonstrated in shoreline outcrops at these localities.

At the Cape Nuvotannak locality it is possible to traverse from pristine Uivak gneisses across zones of progressive reconstitution into typical Iterungnek gneisses. The Uivak gneisses at this locality are grey, somewhat homogeneous, weakly banded, biotite-foliated rocks (Plate 24a) lacking the concordant pegmatites seen at other localities, e.g. south shore of Iterungnek Fiord. Saglek dykes, in various stages of disruption, are abundant, varying in size from a few centimeters to ten meters in maximum dimension. The majority still display the characteristic porphyritic texture, though the feldspar megacrysts are generally elongate, and all are concordant to the enclosing gneissic foliation. A large blotchy-textured pre-Uivak inclusion also occurs in the grey gneisses at this locality.

The Uivak gneisses and concordant dykes are folded in local zones. These folds are considered to be Iterungnek in age, and the gneisses display the green blebby axial planar foliation (Plate 24b) observed in other areas of Uivak remobilization. This fabric discordantly overprints the biotite foliation of the Uivak gneisses. An axial planar fabric is not easily detected in the folded dykes; small thin feldspathic stringers in them have a corrigated aspect in the hinge zones, the corrigations being parallel to the axial plane of the fold.

Adjacent to a large dyke remnant in the Uivak gneisses there occurs a narrow zone (up to 10 m wide) in which the continuity of the rather massive character of the gneisses is disrupted (Plate 25a). Numerous, small irregular sub-concordant granite pegmatites pervade the outcrop. Some of the Saglek dykes in this zone are stretched into narrow lensoid inclusions, others remain as pencil-thin discontinuous stringers. The larger dyke fragments form agmatite horizons, being broken up by granitic veining from the enclosing gneiss.

Westward from this narrow zone of remobilization, the Uivak gneisses are contorted, displaying large, asymmetric "drag folds" with wavelengths of 3.5 m and amplitudes up to 3 m. There is a noticable presence of narrow pegmatites crossing the folded banding, which appear to have formed by segregation of the more mobile constituents in the grey gneiss during folding. This folded zone passes rather abruptly into a linear region of higher deformation characterized by pronounced shearing and transposition of the Uivak gneisses, in which small areas of folded earlier gneissosity are preserved, commonly as intrafolial relics or small enclaves (Plate 25b). The "new" gneisses produced by this transposition of the Uivak foliation are the Iterungnek gneisses. Folds of the preserved Uivak layering in the enclaves have axial planes parallel to the surrounding Iterungnek gneissosity, and have the strongly developed axial planar foliation defined by the green blebs mentioned earlier. With increasing deformation the Uivak intrafolial remnants are extremely attentuated and

PLATE 24

REWORKING OF UIVAK GNEISSES, HEBRON FIORD

24a. Uivak gneisses and Saglek dykes at Cape Nuvotannak locality.

24b. Folded Uivak gneiss/Saglek dykes. Note blebby axial planar foliation.

PLATE 25

REWORKING OF UIVAK GNEISSES

25a. Narrow zone of reconstitution in which Uivak "character" of gneisses is disrupted.

25b. Zone of intense transposition of Uivak gneisses. Iterungnek or superimposed foliation becomes dominant.

sheared, until they are "stretched" into parallism with, and become virtually indistinguishable from, the enclosing Iterungnek banding.

This transformation is accompanied by an increase in the amount of granitic material pervading the outcrop concordant to the foliation. Saglek dykes, though extensively fragmented into trains of inclusions (Plate 26a), retain some relics of their earlier features (e.g. megacrysts) in core zones of larger fragments, but most have been metasomatically (?) altered to small balls of hornblendite, commonly surrounded by a mantle of granitic pegmatite. The penultimate stage in this essentially structural/metamorphic reconstitution process is thus a new banded gneiss (Iterungnek) produced by progressive modification of previously existing tectonites (Uivak gneisses) (Plate 26b).

In the small cove at Jerusalem Harbour there is a narrow zone of exposures which displays a less intense degree of refoliation. The Uivak layering here also contains large rafts of amphibolite believed to be Saglek dyke remnants. The banded Uivak gneisses are traversed by numerous zones of shear (Plate 27a) along which the gneissosity is reoriented, or a new banding is produced (Plate 27b). Small folds in the gneiss occurring between the shears, with axial traces parallel to the shears, contain a blebby green axial planar fabric similar to that described earlier, also parallel to the shear

PLATE 26
ITERUNGNEK GNEISSES

Plate 26a, b. Two photos of Iterungnek gneisses derived through a progressive structural modification of the Uivak gneisses. Note hornblendite pods which are the expression of former Saglek dykes.

PLATE 27

TRANSPOSITION OF UIVAK BANDING, JERUSALEM HARBOUR

27a. Closely spaces parallel shear zones along which Uivak banding has been reoriented and/or attentuated.

27b. New banding produced by the mechanism above, with small enclave of original Uivak banding.

direction. This zone appears to be one of plastic deformation and rotational strain, in which the original layering is reoriented and transposed along a network of shear zones.

(ii) On the west shore of the entrance to Jerusalem Harbour there is field evidence to suggest that locally the Uivak gneisses underwent a transformation to rocks termed Iterungnek nebulitic gneisses by a process of partial melting, with no obvious signs of a strong structural influence. The gneisses here (as described in Ch. III) are best described as lit-par-lit migmatites characterized by a modified Uivak paleosome alternating with a quartzofeldspathic pegmatite neosome. The migmatites pass transitionally into areas of more homogeneous, granular leucocratic rock in which only whisps of the original biotite-rich paleosome remain (cf. Plate 20). It is in these zones that the diffuse-bordered, orthopyroxene-bearing, granitic "sweats" are developed. The foliation which remains in the nebulites is commonly undulating, and "ghost-folds" can be occasionally observed (Plate 28a). Even though most of the original Uivak gneiss has been obliterated, restites of the pre-Uivak mafic inclusions and Saglek dykes remain as hornblende pods (Plate 28b). The impression given by transition zones such as these - from Uivak gneiss through lit-par-lit migmatite to nebulite - is that the older gneiss has undergone *in situ* static partial melting and recrystallization.

PLATE 28

ITERUNGNEK NEBULITES

28a. "Ghost-folds" outlined by biotite in a nebulite zone, Jerusalem Harbour.

28b. Pre-Uivak or Saglek dyke restites in Iterungnek nebulite, Jerusalem Harbour.

The descriptions presented above are considered evidence for the derivation of these areas of Iterungnek gneisses directly by reconstitution of the Uivak gneisses. This new series of gneisses is an inhomogeneous suite on regional scale, and their mode of origin is not always obvious throughout the area. However comparable relationships between Iterungnek and Uivak gneisses at Saglek, some 50 km to the north, indicate that the older gneisses have undergone remobilization over a large area of this part of northern Labrador.

CHAPTER VI

STRUCTURAL GEOLOGY

VI.1. Introduction.

The general pattern exhibited by the geological map (in pocket) of the study area is one of alternating linear units of granitic gneiss, basic gneiss and metasedimentary gneiss. Layering and schistosity attitudes in all gneiss types throughout the region dominantly trend NNW-SSE, with divergences 25-30° East or West, and dip steeply west, commonly vertical. Local variations in strike and dip can usually be attributed to folds post-dating the formation of the regional layering.

The rather limited structural mapping has put constraints on this aspect of the study, and has precluded a subdivision of the area into coherent sub-areas with homogeneous domains. Thus the study area is treated as a single entity, with specific reference to localities where noteworthy structures occur. The deformation is treated in descriptive rather than quantitative terms because insufficient data are available to enable values of the intensity of deformation to be calculated. It is understood however that visual estimates of the intensity of deformation suffered by a rock may be misleading, but it may suffice as a first approximation providing a "stepping-stone" to a more rigorous treatment of the deformed rocks of the area.

VI.2. Terminology Used.

Although a numerical system is commonly used when describing deformations and structures in polydeformed rocks (e.g. D_1, D_2, D_3 ... for deformation; S_1, S_2, S_3 ... for various S-surfaces; F_1, F_2, F_3 ... for fold generations and so on) it may lead to confusion if used to correlate over large areas (see Tobisch and Fleuty, 1969). For example the earliest recognizable structures in the Uivak gneisses at Jerusalem Harbour may in fact be second or third generation features at Saglek, because areas of low intensity Uivak deformation may provide "windows" through which very early deformation patterns in that region may be recognized. Thus within this thesis the S-surfaces[1] which are obviously products of polyphase deformation (i.e., are composite fabrics; Turner and Weiss, 1963, p.41) are designated by a letter (cf. Chadwick, 1968).

The earliest recognisable foliation of mesoscopic or outcrop extent occurs within the areas of Uivak gneisses and is referred to as S_u. Similarly lineations and folds are denoted by L_u and F_u respectively.

Small-scale folds in the Uivak gneisses attributable to the deformation which gave rise to the Iterungnek gneisses (D_I)

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[1] The letter S is used in the sense of Turner and Weiss (1963) to denote a penetrative planar feature. In this area the S-surfaces are tectonometamorphic features (gneissosity, schistosity) and not primary (i.e. bedding, igneous layering).

are termed F_I, and the axial planar foliation in these folds, S_I. Where such folds can be observed in the Uivak gneisses their axes are designated as $\beta_{S_u}^{S_I}$, meaning the axes of folds of the Uivak gneissosity/schistosity with the Iterungnek foliation as the axial surface. The Iterungnek foliation (S_I) is the dominant penetrative fabric throughout most of the area. It is variably developed -- from a biotite alignment discordant to the Uivak layering or its modified equivalent, to an anastomosing fabric in granite sheets, to a regional gneissosity. Most mesoscopic folds in the region have S_I as the axial planar fabric, and are therefore F_I, as are the folds which give rise to the pattern of rock-units on the geological map (in pocket).

Simple folds which affect the Iterungnek layering are termed F_{I+1} and F_{I+2}, meaning two recognizable folding episodes which deform the Iterungnek foliation surface. The axial plane fabric (S_{I+1},S_{I+2}) associated with these folds is not a composite feature, but rather is a simple fabric.

Lineations present in the area may be of several generations. The most common is a mineral rodding or streaking lineation (Type 2 of Weiss, 1958, p.20) in the quartzofeldspathic gneisses defined by streaked out aggregates of quartz and/or feldspar, [illegible] elongate or rodding of these minerals. In the metagabbro sills [illegible], the plagioclase megacrysts form a similar rodding lineation.

An intersection lineation (Type 3 of Weiss, op. cit.), caused by S_I biotite intersecting the Uivak or modified Uivak foliation surfaces, and has been observed to overgrow rodding/streaking lineations on the same surface.

VI.3. Brief Outline of Deformation Concepts.

In the analysis of deformed rocks it has become customary to describe the structures seen in these rocks in terms of the principal strain axes. The concept was discussed in detail by Flinn (1962) and is based on an original sphere deformed into an ellipsoid with principal axes X, Y, and Z such that $Z > Y > X$. The shape of the deformation ellipsoid is described by the K-value defined as $K = \frac{a-1}{b-1}$ where $a = Z/Y$ and $b = Y/X$. For $0 \leq K < 1$ the ellipsoid is oblate (pancake-shaped) and the deformation is a flattening type. For $K = 1$ the deformation is plane at constant volume; all simple shear deformations have this value. For $1 < K \leq \infty$ the ellipsoid is prolate (cigar-shaped) and the deformation is a stretching or constrictional type. In addition Watterson (1968) has defined an "amount of deformation" as $r = a+b-1$.

Rocks which deform plastically may do so in several ways, and since only the deformed state (i.e. the final product of strain) is seen it is difficult to establish the actual movement path(s) which produced this condition. This can be appreciated by considering pure shear versus simple shear.

(Ramsay, 1967). In pure shear the principal strain axes of the deformation ellipsoid maintain a constant orientation throughout the deformation, and consequently this process is referred to as irrotational strain. In simple shear the principal axes change orientation during progressive deformation, and the process is termed rotational strain. The final products of the deformation in each case may be indistinguishable.

In some cases of simple shear (rotational strain) it may be possible to see the shear planes, or deduce their orientation from structures in the deformed rocks. In this situation the deformation may be described in terms of three mutually perpendicular tectonic axes a, b, c (Sander, 1930), where a is the direction of slip or shearing on the shear surface, b is normal to a in the shear plane, and c is normal to the shear plane (ab).

VI.4. Pre-Iterungnek Structures.

Structures which predate the main regional deformation are not common. However the enclaves of Uivak gneisses do contain some mesoscopic examples.

The gneissosity/schistosity of the early gneisses is a composite fabric derived by the transposition and disruption of an earlier compositional layering and various ages of quartz-feldspar veins. Numerous examples of intrafolial interference patterns and rootless folds may be observed in many outcrops (Figure 10). These are generally on the order of a few centimeters in size. The schistosity of the Uivak gneisses is dominantly defined by biotite, but hornblende has been observed in the mafic-rich phases. It is somewhat curious that in all examples of Uivak gneiss encountered the Uivak banding parallels that of the Iterungnek gneisses. However small-scale structures such as fold axes and lineations are south-plunging (Figure 10d) whereas similar linear features in the Iterungnek gneisses are largely north-plunging.

Pre-Uivak inclusions show evidence of folds and planar fabrics which are independent of those in the Uivak gneisses, and are therefore indicative of even older metamorphic/ structural events.

Because of the restricted occurrence of Uivak gneisses investigated, no detailed discussion of the early (pre-D_I) structures can be given. However, the regular gneissic banding with its parallel foliation commonly forming augen around Saglek dyke and pre-Uivak pods and the association of this foliation with intrafolial folds indicate a tectonometamorphic history which involved a flattening type of deformation ($K < 1$) with a component of transposition or shearing.

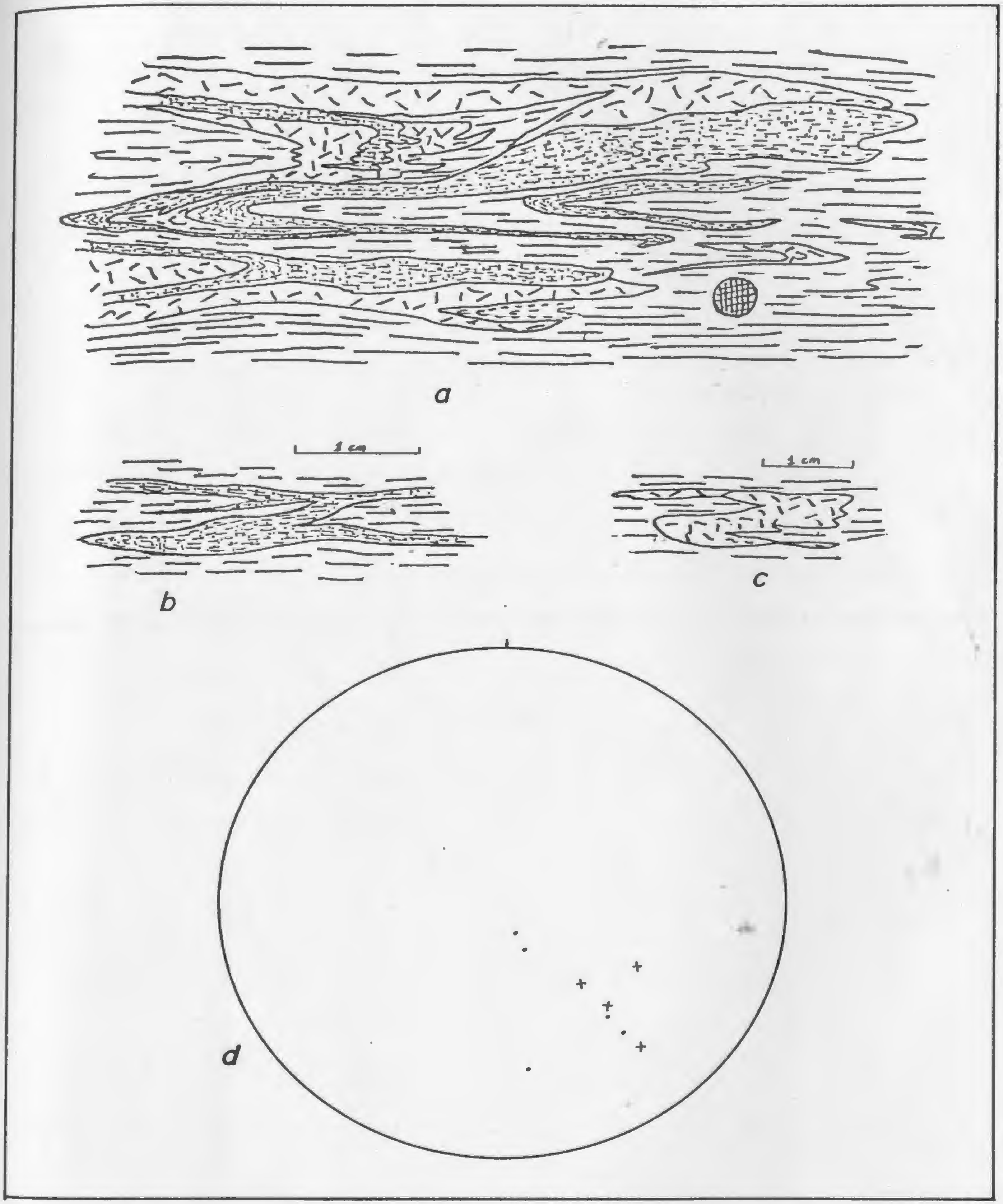

Figure 10. Non-profile views of mesoscopic structures in the Uivak gneisses. (a-c) Intrafolial interference pattern and folds defined by earlier banding and veins. Coin for scale in a is 1 cm in diameter. (d) Stereograph of plunge of lineations (L_u = dots) and small fold axes (F_u = crosses) in the Uivak gneisses.

VI.5. Iterungnek Structures - The Regional Layering.

The regional grain is considered to have been produced as a result of structural/metamorphic/igneous processes active in this part of the North Atlantic Archean craton approximately 3100 million years ago. The gross lithological variations were established prior to this and contain intralithology fold closures which predate the Iterungnek deformation, e.g., refolded isoclinal folds in the layered basic body in Jerusalem Harbour.

The nature of the Iterungnek planar element in the gneisses varies depending on the rock type. Where the earlier Uivak S-surface is preserved S_I is expressed simply as a renewed mineral growth forming a schistosity axial planar to F_I folds in the rocks. However throughout the greater part of the area the main expression of D_I is a distinct compositional layering in the gneisses which may have developed by structural mechanisms like those described in the previous chapter. A strong subvertical schistosity of variable intensity is parallel or slightly discordant to the gneissic banding and is axial planar to small-folds. Exceptions to the banded gneisses are the zones of nebulite and the homogeneous weakly foliated granites.

Two faults running SW-NE through the study area separate blocks between which there is no structural or lithological continuity.

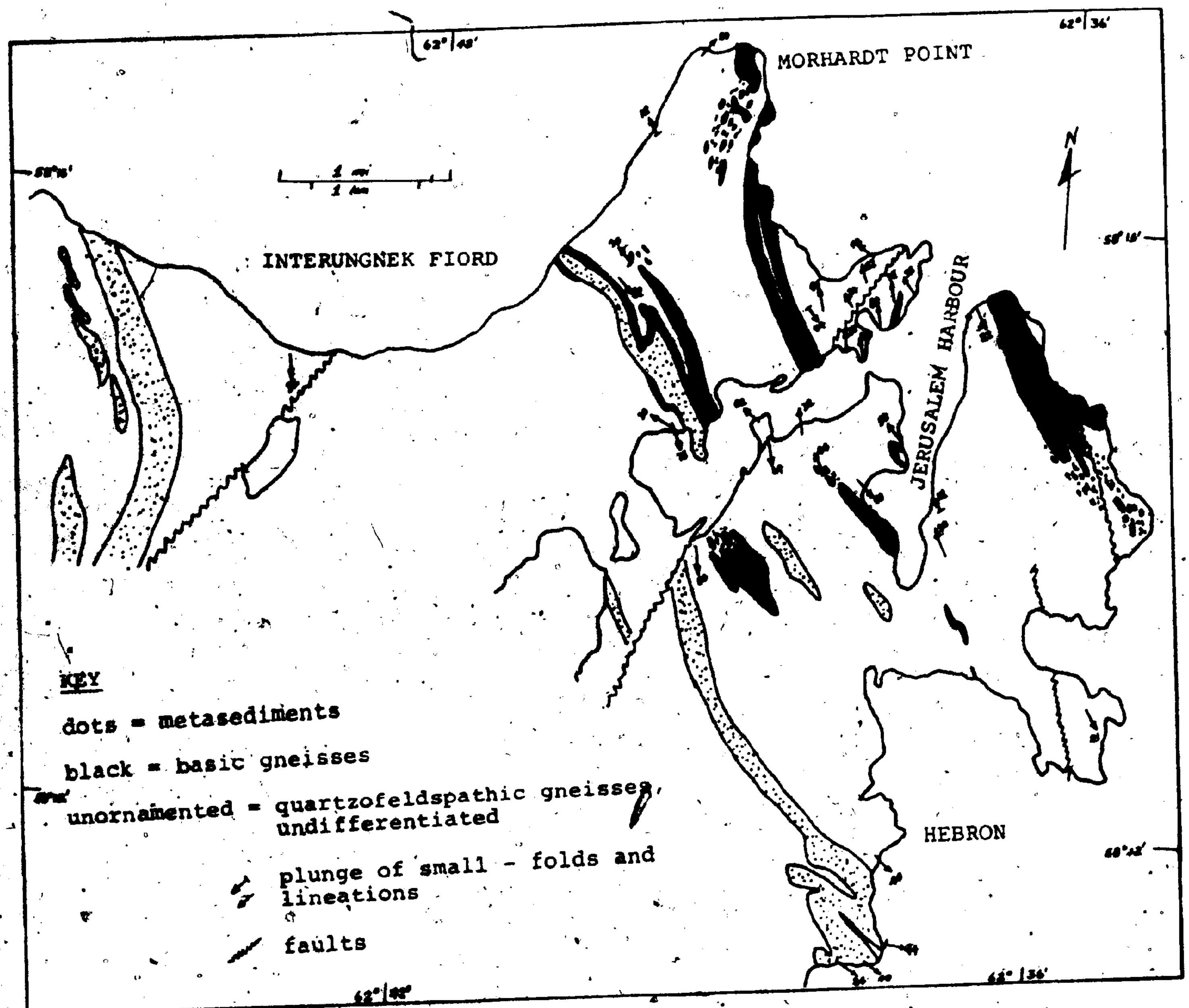

Figure 11. Orientation of fold axes and lineations in the Iterungnek gneisses.

VI.5.1. Mesoscopic Structures.

Structures of Iterungnek age which may be observed in individual outcrops are now described under three headings viz. folds, lineations and folded boudins (Figure 11).

(1) Folds: Most mesoscopic folds which can be "walked-out" on the scale of an outcrop are tight and commonly isoclinal (Fleuty, 1964a) whose axial surfaces parallel the regional layering. It can be shown on the scale of a single outcrop that the limbs of such folds are rotated or tightened into parallelism with the axial plane fabric and the hinge zones gradually destroyed by shearing along the axial surface to produce a new banding (cf. Balk, 1936). In some outcrops fold limbs pass abruptly into shear zones giving a new transpositional layering with only the earlier hinge zones remaining as isolated rootless intrafolial closures.

The style of F_I folds is quite variable (Figures 12 and 13), and depends both on the local tectonic environment and to some extent on lithological differences. Within any one lithology however, F_I folds may very considerably solely as a result of the differing intensity of D_I. In most cases the axial planar schistosity (S_I) is easily detected. Individual folds may be combinations of more than one style. In fact, the style of F_I folds is so varied that they give the impression of being of several ages. However the folds reproduced in the text-figures are all of the same age and demonstrate the errors that may arise by assuming that several fold styles imply several deformations (see also Park, 1969; Williams, 1970).

Mesoscopic F_I folds in zones of high strain and transposition commonly have thick hinge zones and thin attenuated limbs producing class 2 and class 3 folds of Ramsay (1967). In numerous outcrops it can be demonstrated that shear along closely spaced shear-planes (the axial plane foliation) played an important role in the development of these folds (Knopf and Ingerson, 1938; Roberts, 1966; Ramsay, 1967). In Jerusalem Harbour a thin (∿20 cm) mafic band in reworked Uivak gneisses acted as a passive marker during the deformation and became sliced into a series of discrete, semi-continuous pieces by shear displacements along a system of step-like discontinuities giving rise to a structure which may be termed "asymmetric Gleitbretter" (Ramsay, 1967, p.390). In some cases fold hinges have been sheared out completely and S_I is the resulting feature (cf. Figure 13b).

The overall tight to isoclinal nature of the D_I folds, the pervasive nature of the accompanying foliation (S_I) and the numerous examples of transposition of limbs and fold hinges indicate that they formed under strong compressive stress during which shear movements were active. However

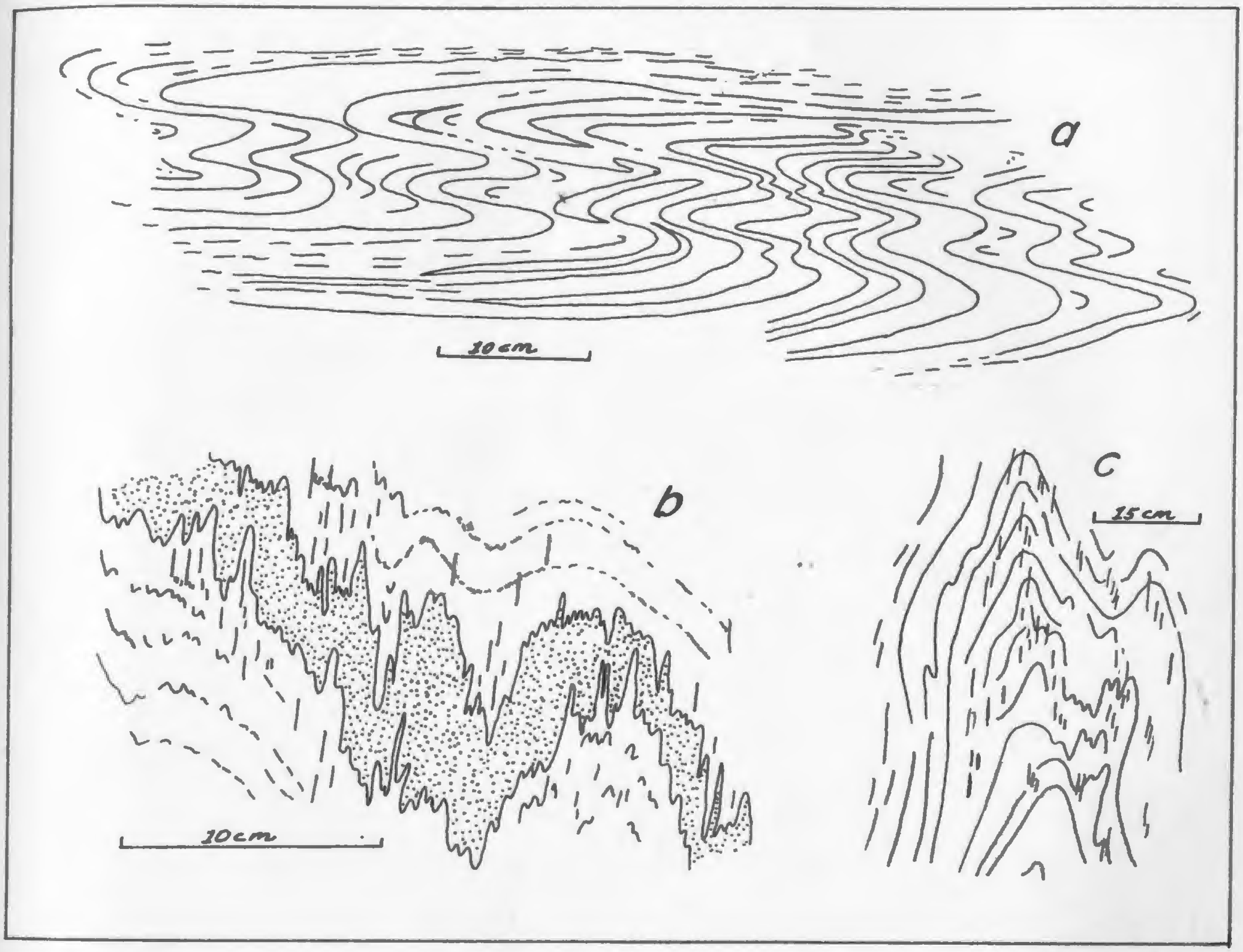

Figure 12. Variations in style of folds developed during the formation of the Iterungnek gneisses (non-profile views).

(a) Interference pattern (Type III of Ramsay, 1967) outlined by biotite foliae in area of reconstituted Uivak gneisses Jerusalem Harbour.

(b) Tight folds in felsic layer in amphibolite. Note strong development of S_I fabric.

(c) Disharmonic fold outlined by biotite rich layers in transposed Uivak banding, Iterungnek Fiord. Note S_I biotite fabric crossing earlier foliation.

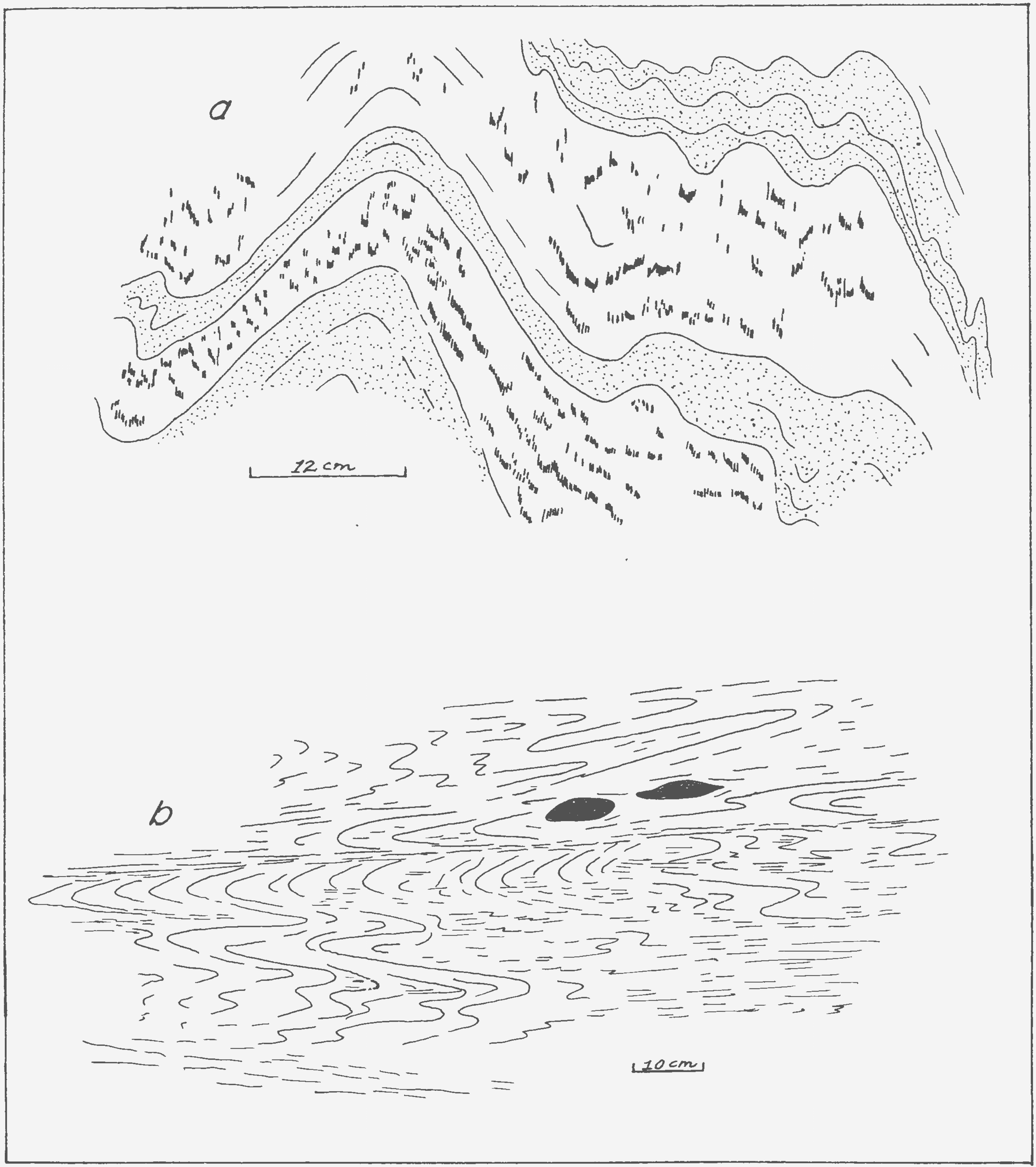

Figure 13. Iterungnek folds (non-profile views).

(a) Flexural type fold in layered basic body, Jerusalem Harbour. Note hornblende alignment in felsic layers.

(b) Shear-folds in partially reconstituted Uivak gneisses, Jerusalem Harbour. Note predominance of S_I over S_u in zones of transposition.

the disharmonic aspect of some folds observed indicates that a component of buckling or parallel folding was also responsible for their formation (de Sitter, 1958).

Although there is a wide scatter in the attitude of axes of F_I folds, there is a consistent NW-NNW plunge direction (Figure 14a) with the exception of one small-fold within the supracrustals at Hebron.

(ii) Lineations: Lineations are not ubiquitous throughout the area, but where observed are a rodding or streaking and intersection type (types 2 and 3 of Weiss, 1958). In contrast to those in the Uivak gneisses described above, the linear elements are dominantly north-plunging, but there are some which are south-plunging (Figure 14b). Even though the streaking lineations are consistently north-plunging in most outcrops, there are departures from this general rule, and directly opposing attitudes may be observed in individual exposures of an otherwise homogeneous gneiss. Collerson, Oliver and Rutland (1972) describe similar variations in lineations from high grade metamorphic rocks from central Australia and attribute them to inhomogeneity of strain during one period of deformation such that the direction of maximum elongation was different in different layers. The L_I streaking lineation is nearly always parallel to the axes of small folds (F_I) and tectonic "b" axis. It therefore appears that a monoclinic symmetry pattern of movement has

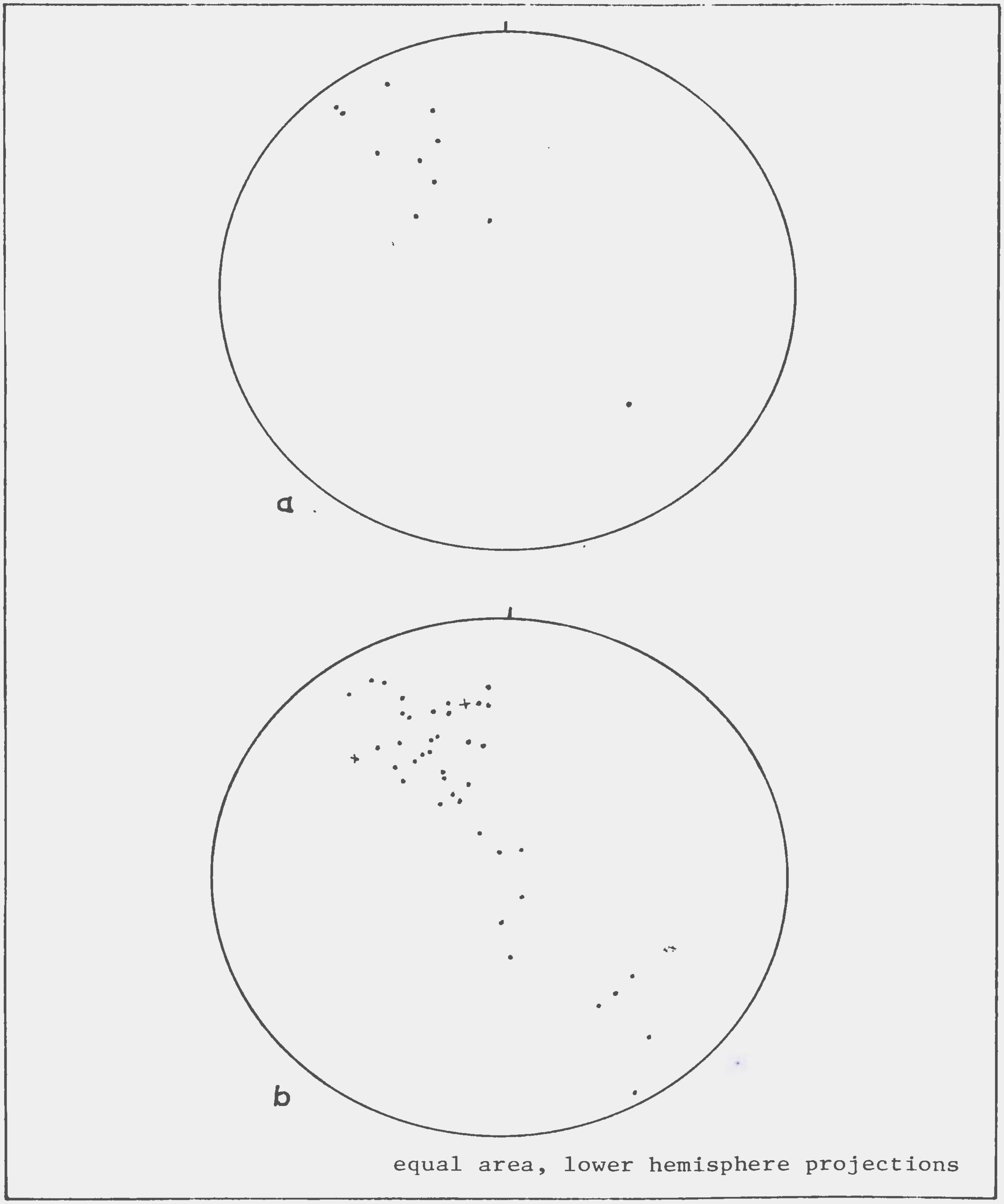

Figure 14. Plunge directions of linear structures in Iterungnek gneisses

(a) Fold axes (includes $B^{S_I}_{S_u}$)

(b) Lineations; dots = streaking or rodding, crosses = intersection.

been active, where the "ab" plane and the YZ deformation plane are coincident, and the translation in this plane is normal to "b".

(iii) Folded boudins: In polydeformed rocks boudins produced during one deformation may be folded during another because of the various attitudes of the superposed strain ellipsoids. However, occasionally folded boudins may be produced during a single progressive rotational deformation (Elliott, 1972). Folded boudins have been observed in the layered basic body in Jerusalem Harbour and in a basic layer in the metasediments at Hebron. The fold axes in both cases parallel F_I folds in nearby gneisses, but it is not possible to state whether these features are a result of two deformations or one progressive rotational stress regime during the Iterungnek deformation.

VI.5.2. Heterogeneous Character of the Iterungnek Event.

Discontinuities and inhomogeneities in the pattern of deformation accompanying the formation of the Iterungnek gneisses are clearly evident in the area. These include the "shearing out" of D_I folds of Uivak gneisses to produce the Iterungnek gneisses, the disruption of inclusions, variable degrees of folding exhibited by the rocks, and the growth of new minerals in the gneisses. Changes in the pattern and intensity of the deformation can be seen in single outcrops in which relics of the Uivak gneisses are preserved. For example, the heterogeneity of the deformation is readily illustrated by the zones of low strain in which the early Uivak banding remains, or where primary igneous structures are preserved in the Saglek dykes and the layered intrusions such as at Hebron and Jerusalem Harbour (Chapter III). These areas contrast sharply with adjacent zones of higher strain in which such features are completely obliterated by the increasing influence of the structural overprinting of the Iterungnek deformation.

The inhomogeneous character of the Iterungnek deformation precludes much discussion of it in terms of the deformation ellipsoid, used when discussing homogeneous strain. However, for the purposes of simplicity, it is convenient to think of the deformation as being homogeneous with respect to small zones (Ramsay, 1967). The nature of the project did not allow quantitative aspects of the deformation to be investigated, but it may be discussed in general terms.

The reorientation of the Uivak banding into parallelism with the Iterungnek foliation, and its complete dismemberment and eventual obliteration indicate that the amount of deformation (Watterson, 1968) was very high, and an estimate of r = 35 comparable to the Vesterland gneisses is certainly in order for the Iterungnek deformation. The character of the Iterungnek deformation, as described from Hebron Fiord (Chapter V), point to changes in "r" on the outcrop scale since areas where Uivak banding is undeformed pass gradationally, but rather abruptly, into zones where Iterungnek effects become dominant and a new banding has developed.

The shape of the deformed megacrysts of plagioclase in the sills at Hebron, and of quartz and feldspar augen in disrupted veins within the plane of the Iterungnek schistosity indicate that this planar feature in the gneisses is parallel to the ZY finite strain plane. Fold axial surfaces are also co-planar with the regional fabric and also indicate that S_I parallels the ZY plane, a feature noted by Ramsay (1967)[1] and demonstrated by the shear belt study of Ramsay and Graham (1970).

The augen in the gneisses and the feldspar megacrysts in the sills form prolate ellipsoids when seen in three dimensions. The absence of a strong planar fabric in the sills, and the presence of the L-tectonite (Flinn, 1965) indicates that they were affected by a constrictional type of deformation ($K > 1$). No cases of extreme elongation were observed, the Z/X values generally less than 10:1. From a general point of view, the feldspars show elongation parallel to the Z finite direction of the D_I strain ellipsoid. XY surfaces commonly show euhedral forms (cf. Plate 14a) with no great variations in dimension, but in a few outcrops it can

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[1]Since the terminology of Flinn is used by the writer, the ZY plane corresponds to the XY plane of Ramsay.

be shown that Y lies parallel to the schistosity and X perpendicular to it. This lineation therefore provides the direction of maximum elongation (Z) during what was apparently a constrictional phase of deformation.

The L > S fabric exhibited by the sills at Hebron is an exception to the general pattern in the map-area which is dominated by a strong schistosity and gneissic banding co-planar to axial surfaces of folds indicating a flattening type of deformation (K < 1).

In summary then it can be said that the relationship between the fabrics and orientation of the deformation ellipsoid on the outcrop scale conform to observations made elsewhere (e.g., Flinn, 1962; Watterson, 1968; Ramsay, 1967) which show that the planar schistosity is parallel to the YZ plane and lineation is parallel to the Z, or maximum extension direction.

VI.5.3. Megascopic Aspects.

It was indicated at the beginning of this chapter that the gneissosity on a regional scale, as well as on an outcrop scale, shows a fairly uniform orientation, a feature also shown by the distribution of poles to banding on the stereographic projection (Figure 15). Few megascopic folds of the layering are present, but where marker horizons defined closures, the folds exhibit tightly appressed limbs and very narrow tight hinge zones. This situation is also

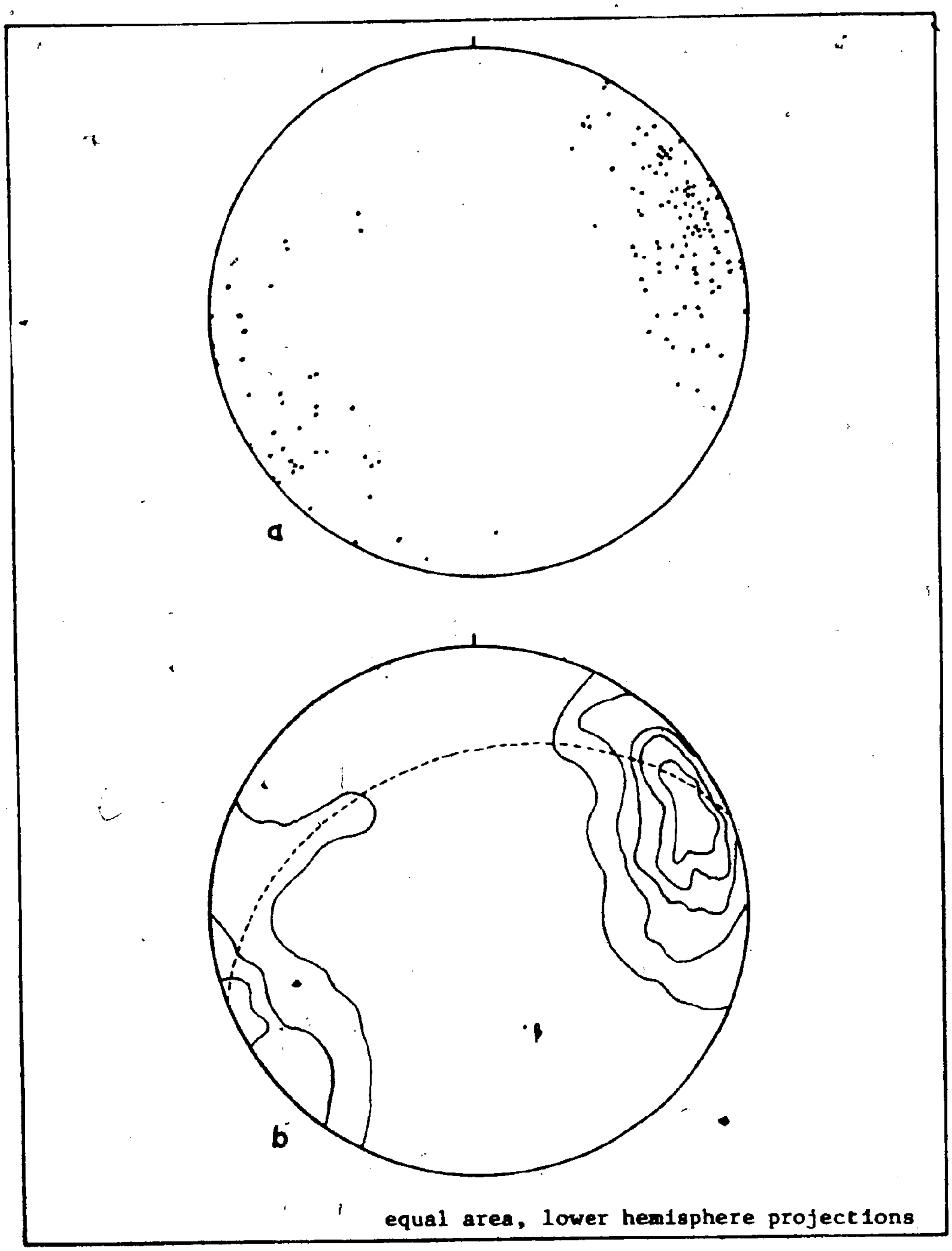

Figure 15. (a) Poles to gneissic layering in all lithotypes in the area (157 points).
(b) Contoured diagram of above. Contours enclosing 1, 4, 6, 10 and >15 points per 1% area. Dashed line represents a possible great circle for the distribution of the poles.

reflected in the orientation diagrams which exhibit a monoclinic fabric symmetry (Turner and Weiss, 1963, p.66) of the type which would be expected in an area of tightly appressed similar-type folds. The absence of a well-defined great circle distribution is due to the fact that only a few gneissosity attitudes have been obtained from the actual closure zones, and therefore the diagram is biased towards the more widespread orientations of the layering on the limbs.

The general NNW-SSE trending nature of the regional foliation is somewhat curving as shown by the distribution of lithologies and gneissosity orientations (see map in pocket), and is especially apparent in the marked divergence of units on Morhardt Point. It is possible that these varying orientations are due to large interference structures (eye-folds) caused by a later phase of folding on the regional layering, the continuation of the outcrop pattern produced by the structures being outside the study-area. Alternatively the divergence may be a product of the Iterungnek deformation. If the Iterungnek folds are non-cylindroidal, due to triaxial compression during D_I, the doubly plunging attitude would cause the same pattern.

The axial plunge of the major fold structures at Hebron, based on the changing orientation of the gneissic banding and small-folds in the area of fold closures is South at 40-45°. A similar fold structure on the north side of Jerusalem Harbour also plunges southward, but at a slightly greater angle (~75°).

The southward plunging character of the megascopic structures is therefore in contrast to the attitudes of most small-folds and lineations in the area, which are N plunging. Such a pattern suggests several possibilities for the relationships between the mesoscopic and megascopic structures. For example (i) the lineations and small folds all pre-date the Iterungnek deformation (ii) the regional folds post-date the Iterungnek deformation or (iii) both mesoscopic and megascopic structures are the same age but have this relationship due to some unique character of the Iterungnek deformation.

The first suggestion is considered unlikely on several lines of evidence. The lineations are all found on the Iterungnek gneissosity planes and are therefore considered related to this S-surface. Similarly small folds are most abundant in zones where the Uivak layering is undergoing transposition and being replaced by the Iterungnek gneissosity, and are therefore also of Iterungnek age. Finally the metamorphic/structural overprint of the Iterungnek event has been sufficiently pervasive such that very few earlier structures remain in the reworked gneisses.

The second possibility is considered unlikely because all folds which have been "walked-out" in the field have the Iterungnek schistosity as the axial planar foliation and are therefore Iterungnek in age, unless a later phase of folding co-planar with the Iterungnek folds has occurred (cf. Park, 1969). There is no definite evidence for co-planar folding.

It is therefore concluded that the relationship between the Iterungenk mesoscopic and megascopic structures is due to a special relationship between the pre-Iterungnek lithological layering orientation and the D_I deformation ellipsoid. It is postulated that the lithological layering at the onset of the Iterungnek phase of deformation was inclined at some unknown angle to the Z direction of D_I. Structures thus initiated in the zones of reworking (e.g., small-folds, streaking lineations) were parallel to the major axis of the D_I strain ellipsoid (cf. Schwertdner, 1973, p.1240), but megascopic rotation of the lithological layering on a regional scale was not accomplished. Therefore only the mesoscopic structures show parallelism with the Z(b) direction. The inconsistency in the plunge of small-scale structures versus the megascopic folds is thus a consequence of the attitude of the layering prior to D_I, and the amount of rotation undergone by the layering with respect to the D_I strain axes.

VI.6. Possible Model for the Structural Evolution of the Iterungnek Gneisses.

From the descriptions presented above the writer has attempted to construct a tentative model to explain the features of the deformation accompanying the refoliation of the Uivak gneisses. Firstly, however, the pre-Iterungnek complex must be considered.

Following the model of Bridgwater et al., (1974) we may assume that circa 3.6 billion years ago, there was a major period of crustal instability during which the Earth's crust was intensely deformed. Previously existing metamorphic complexes, igneous suites, and cover rock sequences were interleaved in such a manner that very few vestiges of original stratigraphic relationships remained. This could have occurred through the horizontal regime envisaged by Bridgwater et al., (op. cit.) or possibly through vertical movements. Whatever the process, or processes, whole stratigraphic successions were telescoped and juxtaposed against each other in a series of independent structural slices such that all continuity between formerly continuous sequences was nearly completely obliterated. The interleaving and juxtaposition of various lithologies was probably due in a large degree to megascopic shear and transposition, and tectonic sliding (Fleuty, 1964b) in tight folds. Tectonic sliding cannot occur during homogeneous deformation because the latter is wholly a process of shape change. Therefore this feature, along with the mesoscopic evidence from the Uivak gneisses of rootless intrafolial folds and primary relationships between gneisses and Saglek dykes, points to the inhomogeneous character of this period of deformation.

By 3.1 billion years ago (Hurst et al., 1975) the previously established horizontally (?) layered crust had again become unstable, probably a "softening" effect due to the build-up of radiogenic heat. Calc-alkaline magmas were emplaced along structural discontinuities in some areas of the crust (e.g., Greenland; Myers, 1976) but in other areas of which the study area is one the older sialic crust became reactivated and underwent a structural and metamorphic transformation.

The Iterungnek deformation is considered to have been a long and continuous process which probably began under a constrictional (K > 1) regime, with a linear fabric being of greater importance than a planar one. Subsequently a process of simple shear (K = 1) became dominant during which the Uivak gneisses structurally reworked, and their original character obliterated by transposition. Tight isoclinal folds with steeply dipping axial planes were produced, and "similar" folds formed by translation along the kinematic ab plane were accompanied by a strong rodding and streaking lineation on the transposition surface. The varying attitudes of the lineation are possibly an indication that there is some degree of rotation or change in the strain axes in the ab plane during the transposition of the Uivak banding. Although there is a good agreement between the mesoscopic linear structures, they have an opposite sense of plunge to the regional folds. This is taken to indicate that the previously established lithological layering was not regionally reoriented during D_I. However in the narrow zones of most intense deformation, all earlier Uivak layering has been folded and transposed into parallelism with the kinematic ab plane. The areas where the unreworked Uivak gneisses remain in which the Uivak layering parallels the surrounding Iterungnek layering may be kernels (of early fold closures?) where the original attitude of the Uivak foliation and the Iterungnek a-direction coincided, and consequently the layering was not folded and sheared-out, but was simply attenuated.

The strong gneissic layering in the Iterungnek gneisses is possibly indicative of a final flattening ($K < 1$) deformation. This is apparent in the parallelism of all planar structures in the areas where the Iterungnek gneisses are best developed. When looked at on a regional scale, these areas appear to be tight synformal regions between more open antiformal domes in which Uivak gneisses still remain. These synformal regions are in many respects analogous to the straight belts of Hepworth (1967) and synformal zones of Coward (1973a) in which all indications of the earlier layering have been obliterated, and replaced by the Iterungnek foliation.

The S > L regime has practically obliterated all indications of the initial constrictional deformation. However the metagabbro sills at Hebron have escaped this flattening to some degree, possibly having become more isotropic as a result of recrystallization. These rocks retain the L > S fabric more than any other in the gneiss complex.

VI.7. Folds Post-dating the Regional Layering.

Two generations of folds affecting the Iterungnek layering have been identified. Both are open folds, but their attitudes differ radically.

(i) The first period of folding to affect the regional gneissosity occurred on horizontal axes and produced folds with flat-lying axial planes (recumbent folds of Fleuty, 1964a). Very few folds of this generation (F_{I+1}) were observed during the course of the field study; their usual manifestation is as broad warps on cliff faces perpendicular to the strike of the layering. The few mesoscopic folds of this age which were recognized vary from open to fairly tight (Figure 16a), and

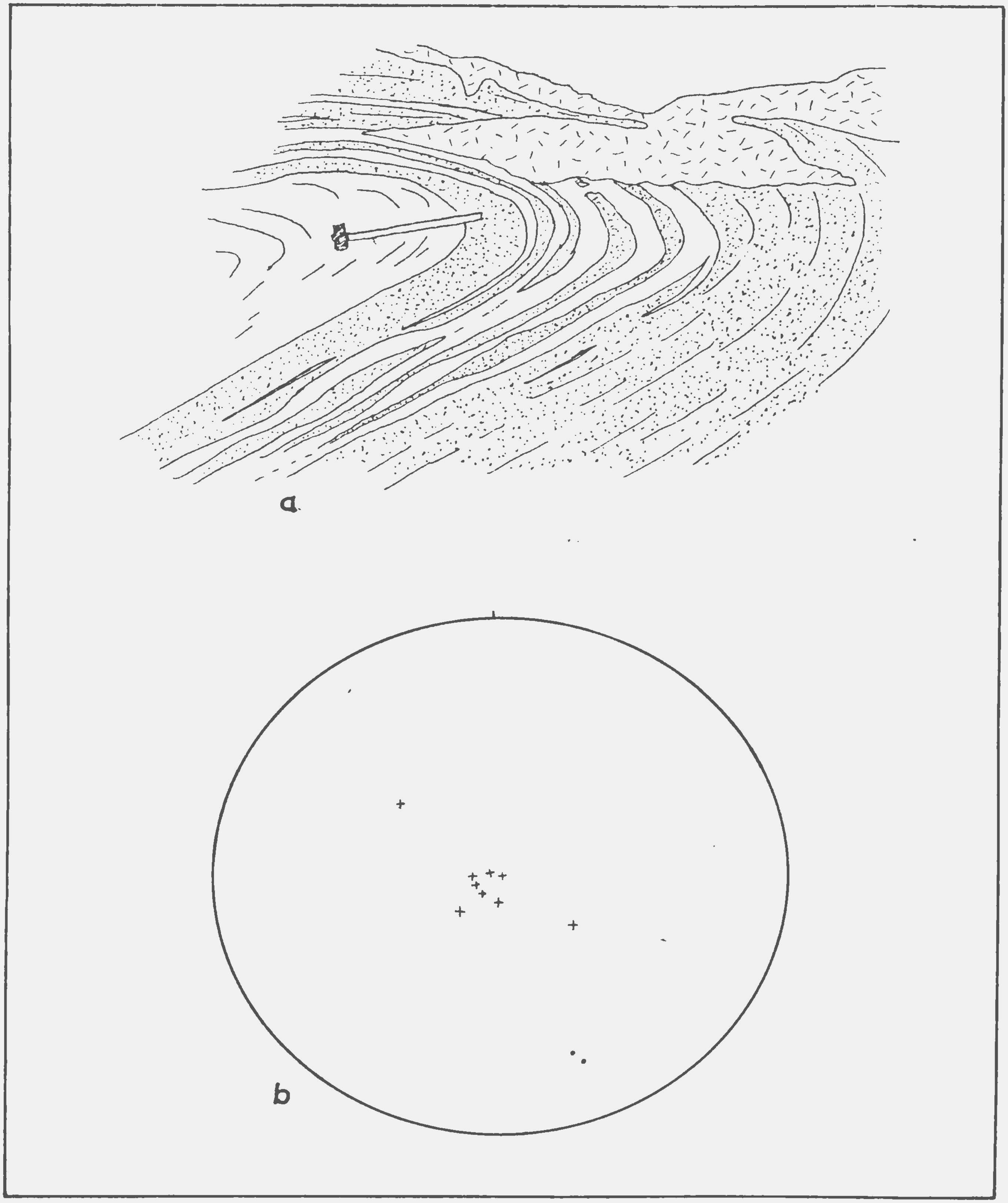

Figure 16. (a) Recumbent fold (F_{I+1}), plunging away from observer $\sim$20°, at amphibolite (dotted)/quartzofeldspathic gneiss contact on shore at Morhardt Point. Large biotite pegmatite at top of sketch. Hammer $\sim$1m in length. (b) Variations in S_{I+1} cleavage, plotted as poles (crosses) and $\beta_{S_I}^{S_{I+1}}$ (dots).

lineations on the gneissosity planes are folded around the fold hinges. The tighter F_{I+1} folds have a prominent axial planar cleavage (S_{I+1}) in the hinge zones, but this dies out quickly away from the actual closure. Measurements of the attitudes of this cleavage and the plunge of the axes of the F_{I+1} folds indicate that they may have been affected by a later deformation which reoriented them (Figure 16b). In areas where the fold axes are horizontal and north-trending, the cleavage seldom exceeds a dip of 10°E. However, folds of the same age have been observed to plunge up to 30°S, and in such cases the cleavage strikes NE and dips up to 45°SE.

(ii) The youngest folds which can be identified in outcrop in the map-area are structures with moderate to steeply plunging axes and steeply inclined axial planes. Measured axes plunge 35-67° Southwest and Northwest; axial planes are generally East-West and dip 55-80° North and South. According to Fleuty (1964a) these features constitute moderately to steeply inclined, moderately to steeply plunging folds. The F_{I+2} folds do not appear to greatly affect the megascopic pattern previously developed. Their most common expression is as gentle warps of the layering, having wave-lengths of <5m to tens of meters; however several smaller mesoscopic structures of this generation have been observed. (Figure 17).

Dip isogons (Elliott, 1965) on line drawings of colour slides taken looking down the fold axes show little variation in the type of fold developed in the rocks as a result of this period of deformation (Figure 18). The isogon arrays indicate that most are of classes 1b and 1c of Ramsay (1967, p.365), that is, are largely flexural folds, possibly slightly modified by a superimposed component of homogeneous flattening (Ramsay, 1967, p.415). Some of the tighter folds in the quartzofeldspathic gneisses (Figure 18c,d) tend toward similar folds (class 2) in their hinge zone, i.e., the isogons approach parallelism.

The F_{I+2} folds have no pervasive penetrative fabric associated with them; however a widely space fracture pattern, occasionally showing a fanning aspect, is developed in the hinge zones of the folds (Figure 17).

On some of the foliation surfaces which have been folded by these late open folds, earlier streaking and rodding lineations are reoriented around the hinge of the fold. The changing attitude of the lineation was measured at four locations around one broad, open, mesoscopic warp of flexural aspect in order to determine the pattern which the folded linear fabric defined. The stereographic plot of the lineations around the calculated β-axis for this fold (Figure 19a) appears to conform to a locus in space around the F_{I+2} axis in a manner similar to that outlined by Ramsay (1967, pp.466-68, 546-48). [Compare also Coward (1973, p.151)]

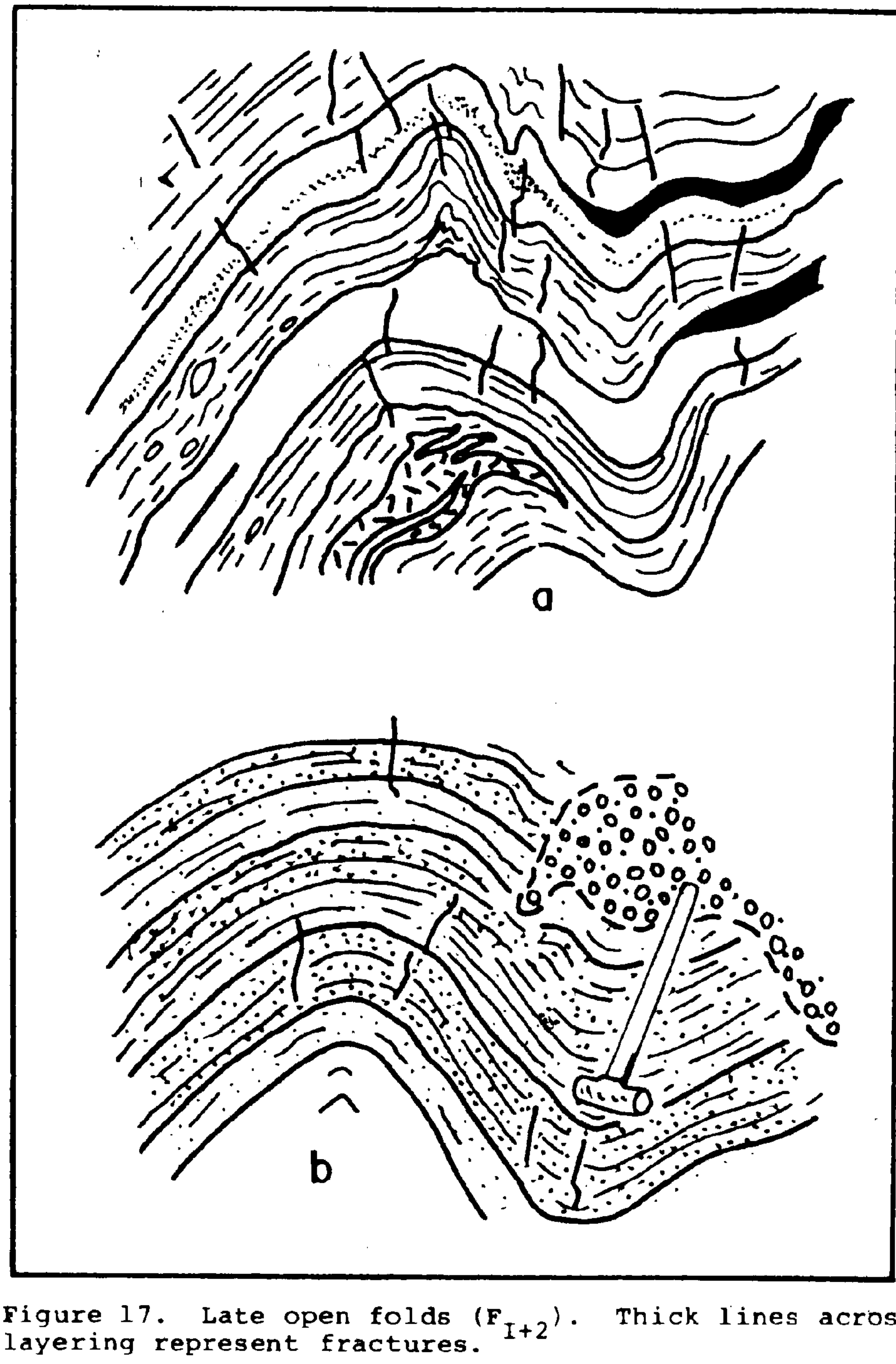

Figure 17. Late open folds (F_{I+2}). Thick lines across layering represent fractures.

(a) Open fold on coast in Jerusalem Harbour. Dark layers at upper right are attentuated Saglek dykes. Pencil in unshaded layer at left is 10 cm in length.

(b) Fold in amphibolite, Morhardt Point. Sledge hammer is 1 m in length. Glacial debris in upper right.

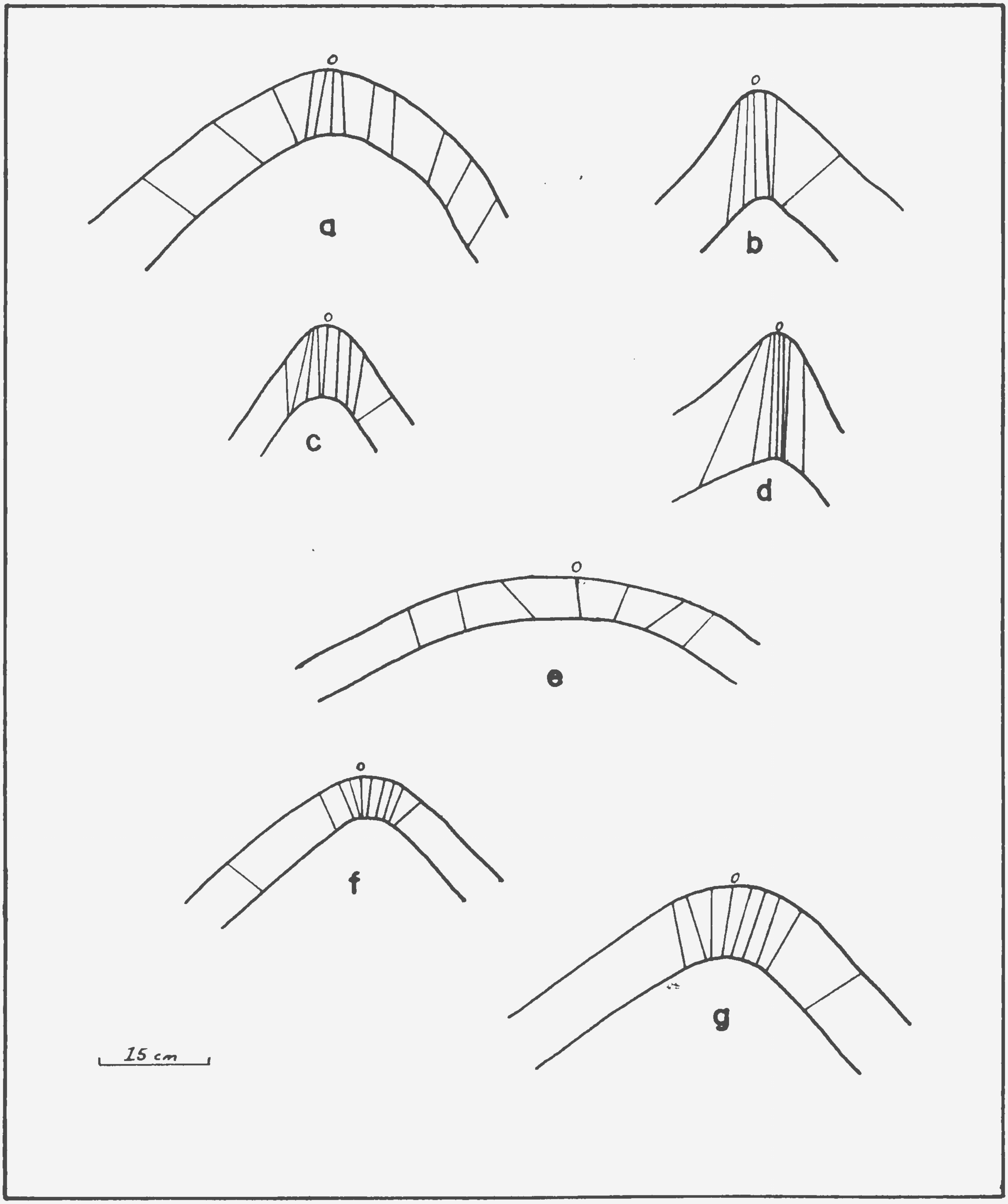

Figure 18. Dip isogons at 10° intervals for approximate profile views of layer folded by F_{I+2} folds. Various localities north and west of Jerusalem Harbour.

Unfortunately the open style of the fold studied and the steeply dipping foliation surface which it deforms, makes it difficult to measure the plunge of the fold's axis directly in the field, and the β-axis used in the construction is derived from a π-diagram. Even with these limitations, the stereographic plot demonstrates the folding of the lineation around the fold axis in a pattern which would be expected from the geometric arrangement of $\beta_{S_I}^{S_{I+1}}$ and the earlier linear structure.

The fact that these late open folds locally plunge both north- and southwest within tens of meters of each other, yet the earlier lineation maintains a constant overall direction in such areas may indicate that this folding was not strictly cylindroidal, but had a conical component to it. This is also suggested by the wide scatter of poles to the gneissic layering (S_I) which were "walked-out" in the field (Figure 19b). If folds are true cylindrical the π-diagram should form a well defined great circle (Weiss, 1958).

VI.8. Summary of Structural Development.

The main points arising from the interpretation of the structural data may be summarized as follows:

The enclaves of Uivak gneisses indicate that S_u is a composite flattening fabric derived from the transposition of earlier S-surfaces by heterogeneous deformation. No

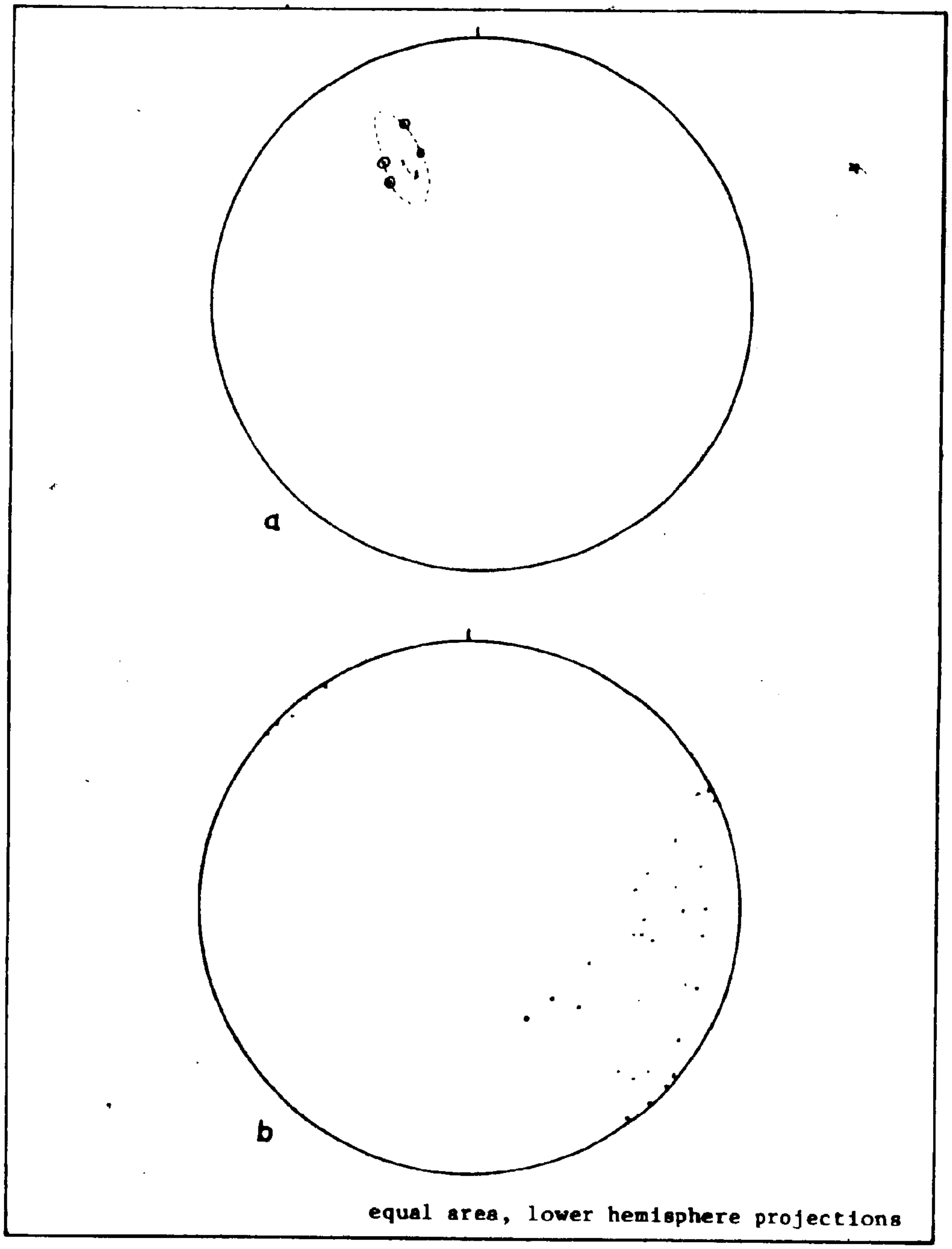

Figure 19. (a) Streaking lineations on Iterungnek gneissosity surface folded around an open F_{I+2} warp.
(b) Poles to gneissic banding of an open fold (F_{I+2}) walked out in the field. Entrance to Jerusalem Harbour.

regional folds of Uivak age have been identified.

The gneissic layering produced by D_u has been affected by a later phase of deformation (D_I) during which the Uivak gneisses were reconstituted to produce a new suite of tectonites, the Iterungnek gneisses. Folding during D_I was commonly isoclinal, though variations in style are present due to varying intensity of D_I and lithologic compentency. Shear parallel to the F_I axial planes was instrumental in the refoliation of the earlier Uivak gneisses. Lineations and small-fold axes are dominantly NW plunging, but regional folds are SE plunging. This is tentatively interpreted to represent incomplete reorientation of the previously existing layering into parallelism with the principal planes of the D_I deformation ellipsoid due to the inhomogenity of the Iterungnek deformation. In zones of intense deformation all structures are parallel to principal planes of the D_I ellipsoid.

It appears that the Iterungnek event was a prolonged phenomenon, and varied from a regime of constriction through simple shear to one of flattening. This is interpreted as representing the progressive "squeezing-in" and refoliation of the Uivak gneisses in tight synformal zones between broad antiformal domains in which there is little effect of D_I.

Two generations of post-D_I open folds have been recognized.

F_{I+1} are recumbent structures on horizontal axes, whereas F_{I+2} are inclined, steeply plunging structures. Only mesoscopic examples of both are present, and no megascopic equivalents have developed in the study area.

CHAPTER VII

SUMMARY AND DISCUSSION

VII.1. Introduction.

This thesis has presented an account of metamorphic and structural processes in early Archean rocks in a small portion of the Nain structural province of Labrador, the western edge of the disrupted North Atlantic craton. It has been shown that geological events in the area 3.1 b.y. ago can be interpreted in terms of the structural reworking of pre-existing Archean crust. The data presented are summarized below, and a brief discussion of its bearing on Archean crustal development is given.

VII.2. Summary.

The bedrock geology of the area around Jerusalem Harbour is dominated by an inhomogeneous series of quartzofeldspathic gneisses of several ages, with intercalated linear supra-crustal belts.

The earliest recognizable quartzofeldspathic gneisses are the 3.6 b.y. Uivak gneisses which occur as restricted linear kernels in younger gneisses. The major portion of these younger tectonites, termed the Iterungnek gneisses, can be demonstrated to have been derived from the older suite by a combination of metamorphic/structural and anatectic processes approximately 3.1 b.y. ago.

The areas of Uivak gneisses are not extensive enough to determine with certainty in the field whether they belong to the Uivak II suite, but petrography has indicated the existance of both suites. The Uivak gneisses are biotite-rich, layered rocks of tonalitic to ferrodioritic composition, and are delineated on the basis of lensoid fragments and inclusion trains of porphyritic amphibolite derived from a disrupted basic dyke swarm - the Saglek dykes.

The gneissose rocks which develops from the remobilization of the Uivak gneisses has been shown to be variable in appearance, in many cases due to its mode of development. The streaky gneisses commonly retain areas where the new gneissosity can be seen to have developed by a shearing and attenuation of the earlier Uivak layering. Small enclaves of the original gneiss, crossed by a new biotite foliation parallel to that of the surrounding gneiss, may be seen. In areas of structural modification it has been shown that the Uivak banding has been reoriented and replaced by the Iterungnek banding chiefly through a shearing mechanism which progressively obliterated the earlier gneissosity. On the other hand, nebulites and lit-par-lit migmatites appear to have formed by <u>in situ</u> static anatexis of the earlier gneiss. In most cases the contacts between the Uivak and Iterungnek gneisses are gradational over a distance of a few meters, and all stages of reworking may be observed in a single outcrop. The rock type which prevails in any one area is a consequence of the degree of remobilization or partial melting which the earlier rocks have undergone, and its structural position within the complex. For instance, the nebulites commonly occur in linear zones parallel to the gneissic layering, a feature suggesting that the degree of partial melting was influenced by the local metamorphic conditions.

Only three areas of Iterungnek gneisses can be demonstrated to have a definite intrusive aspect, namely the foliated granitic bodies which raft-off and incorporate large blocks of basic gneisses on Morhardt Point and Mount Jerusalem, and blocks of metasediments on the south side of Iterungnek Fiord.

Rocks of supracrustal origin (the Upernavik Supracrustals) form five linear belts in the map-area. Three are dominated by metasediments; the other two are basic gneisses. The metasediments are chiefly of pelitic and semi-pelitic compositions, with minor marble and psammite. Coarse porphyritic meta-melagabbro sills occur in the metasediments at Hebron. The basic gneisses are a variety of types, and commonly contain orthopyroxene and/or clinopyroxene in addition to hornblende and plagioclase.

Ultramafic pods occur within the basic gneisses, along the margins of the basic gneisses, and within the quartzofeldspathic gneisses. Though most are isolated tectonic pips, an ultramafic body retaining igneous cumulate textures occurs in Jerusalem Harbour.

There is little doubt that the present mineral assemblages in the rocks of the area are polymetamorphic. Detailed petrographic study of all the major rock types indicate that the Iterungnek gneisses formed under conditions of the granulite facies, and that this metamorphism was superimposed on an upper amphibolite assemblage. An estimate of metamorphic conditions has given P = ∿10kb and T = 825 – 850°C, which if translated to a crustal thickness, indicates a value of ∿30 km. Mineral reactions observed in thin section can be accounted for by the breakdown of amphibolite facies assemblages under a prograde metamorphism resulting in granulite facies assemblages, which experienced incipient retrograde metamorphism during the waning stages of deformation. Most lower grade minerals however, appear to be due to post-Iterungnek retrogression(s).

It is interesting to note that if this 3.1 b.y granulite facies metamorphism is substantiated by future work, then this area of Labrador shows the earliest record of widespread granulite facies metamorphism in the North Atlantic Craton.[1]

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[1] As pointed out earlier in the thesis (p. 61) Collerson has found relic granulite facies assemblages in pre-Uivak inclusions, and McGregor (K.D. Collerson, pers. comm., 1977) has found similar features in pre-Amitsoq inclusions. The full significance of this very early granulite event has yet to be investigated and evaluated.

It is currently considered that a "blanket" granulite metamorphism of "worldwide" dimensions occurred at 2.8 b.y. due to a thickened and stiffened crust at this time (cf. Bridgwater et al., 1973b, p.495). However given sufficient heat flow in the early Earth, it is not necessary to have a thick crust to generate anhydrous assemblages. In any case, the estimates of crustal thickness given above indicate a sialic crust at 3.1 billion years ago which is comparable to that of the present day.

The structure of the gneisses in the map-area is complex, and only very tentative overall conclusions can be drawn from the data obtained during the field study. However, it is obvious in the field that the reworking of the Uivak gneisses was a very inhomogeneous process, during which progressive simple shear played an important role in transposing, reorienting and/or obliterating earlier structures.

Mesoscopic folds on the Iterungnek gneisses are generally very tight similar or isoclinal varieties; variations are chiefly dependent on the intensity of the deformation. In most cases the regional layering can be shown to result from intense deformation whereby the Uivak layering is drawn out on the limbs of folds to produce the Iterungnek compositional banding. The fold styles in general point to a shearing process as being the major mechanism for their development, but the parallel and disharmonic style of a number of F_I folds suggest that buckling or flexural slip was locally operative.

The variations in fold style, related to the intensity of the deformation, may be a result of their evolution by a progressive mechanism suggested by Wilson (1961, p.493) whereby once a schistosity is developed in a folded layer, further movement occurs by laminar slip along the schistosity and the folds progress from flexural slip to shear folds.

The folding during the Iterungnek event took place on subvertical axial planes, and the complete parallelism of structures in straight belts in synformal regions suggests a type of "pinching-in" under horizontally directed stress. The open antiformal regions are areas where the Uivak gneisses are best preserved. Although the interpretation is tentative, the D_I event may be envisaged as a progressive change from a regime of constriction to one of flattening.

The Iterungnek layering has been folded by locally developed open to tight recumbent folds; the tighter structures have an axial plane cleavage which disappears away from the hinge zones. Post-dating these recumbent folds are a set of open flexural folds on nearly vertical axes.

VII.3. Discussion.

It has been pointed out several times in this thesis that the Saglek area displays a geological development in early Archean time which is nearly identical with that experienced by the Godthabsfjord area of southwest Greenland, and this similarity has been repeatedly stressed by Collerson and his co-workers in references already cited. The one major difference in the chronological/lithological development is the apparent diversity in the nature of the 3.1 b.y. tectonic event in both areas. Field evidence presented by most workers in Greenland indicate that a large proportion of the gneiss complex there is composed of rocks derived from calc-alkaline magmas emplaced into the crust as horizontal sheets 3.1 b.y. ago (cf. McGregor, 1973; Bridgwater et al., 1974; Myers, 1976). Others, however contend that there was considerable remobilization of the older gneisses during the formation of the younger suite (Chadwick et al., 1974b; Chadwick and Coe, 1975). The 3.1 b.y. gneisses in Greenland have been termed the Nûk gneisses (McGregor, 1973). By contrast, the younger Archean rocks in the areas of Labrador so far mapped seem to have been derived by various degrees of reworking of the older Uivak gneisses, with igneous activity being of subordinate importance, at least at this level of crustal exposure. These 3.1 b.y. gneisses in Labrador have been termed the Iterungnek gneisses, equivalent to the "undifferentiated gneisses" of Hurst et al., (1975), and have an initial strontium ratio of 0.7065 (Hurst, et al., op.cit.). Since there is no conclusive evidence to demonstrate massive injections of mantle-derived granitic rocks into the crust of Labrador at this time, it is suggested that the Labrador and Greenland Archean suffered differing effects from a period of crustal mobility 3.1 b.y. ago. An attempt to reconcile this difference is presented as a simplified cartoon in Figure 20. A horizontally layered crust (sensu Bridgwater et al., 1974) probably developed around 3.6 b.y. ago. It is considered that the interleaving of sialic and supracrustal material took place at this time, and was accompanied by syntectonic amphibolite(-granulite?) facies metamorphism at depths presently exposed. Layered basic bodies and ultramafic cumulates were emplaced into the "layer-cake" at this time along structural discontinuities created by the tectonic sliding in cores of nappes and transposition between rock units. Workers in the Greenland Archean consider that the interleaving or thrusting took place prior to the major period of metamorphism. However, the existance of large tectonic inclusions of one rock type in another and the lensoid form of the lithological units on all scales suggest plasticity of the rock pile during the interleaving. It is difficult to envisage such a process of attenuation and juxtaposition of units without any metamorphism in an early ductile crust. Therefore the 3.6 b.y. age from the Amitsoq and Uivak gneisses is considered to be a metamorphic age which also dates the time of interleaving. Bridgwater and Collerson (1976) suggest that the 3.6 b.y. age represents a period of Rb addition to the crust, and it is conceivable that the ductile interleaving, metamorphism and Rb metasomatism are concommitant events.

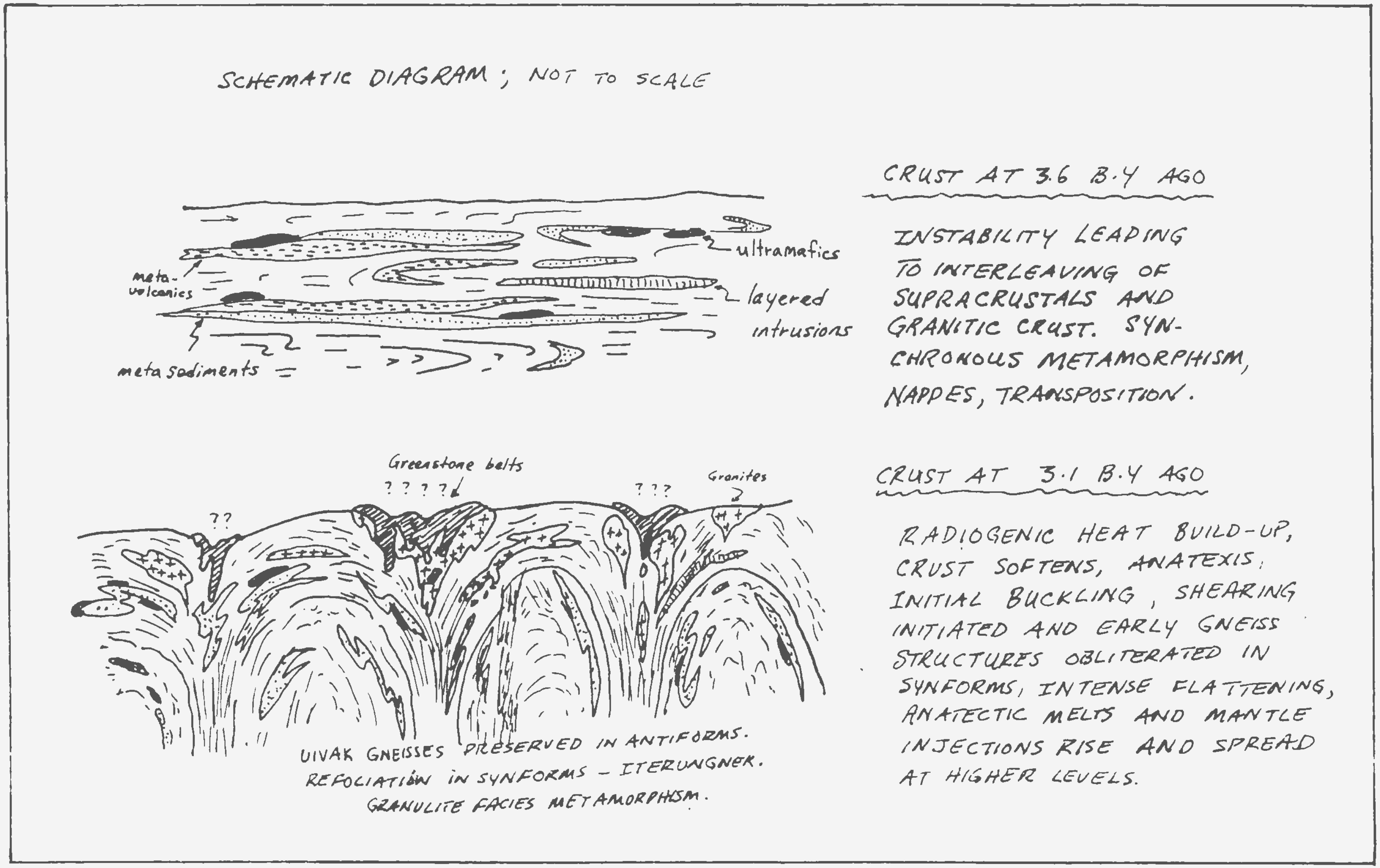

Figure 20. Schematic diagram to illustrate how the horizontally layered crust at 3.6 b.y. ago underwent reconstitution at 3.1 b.y. ago by "collapse" along tight synformal zones. These synforms were the sites of refoliation and migmatization of the older gneiss suites and avenues for upward migration of granitic material.

By 3.1 b.y. ago however, the crust had again become unstable, probably due to a gradual softening caused by heat liberated by radioactive decay of minerals in the mantle and crust, and it (the crust) "gave way". If volcanic supracrustal piles (greenstone belts) had accumulated at the surface between 3.6 and 3.1 b.y. these would have contributed to buckling and the development of shear zones. The earlier sialic crust underwent reworking at depth, with shearing and transposition in narrow synforms; the marginal antiformal massifs largely retain the earlier gneissic structures, but zones of overprinting can be distinguished. The reworking and anatexis of the sialic crust led to granitic (s.l.) melts which joined mantle derived injections of tonalitic material migrating upward. These gave rise to the sheetlike form of the granites in the Greenland Archean since they tended to be confined to available structural discontinuities. This implies that areas of reworking, such as the study area, are at slightly deeper levels than the equivalent rocks in Greenland, a postulate which is also suggested by the granulite facies metamorphism.

If greenstone belts had formed at the earth's surface prior to the reworking, then the tight synformal shear zones at depth provided ductile avenues for gravitational collapse of the overlying supracrustal pile, and simultaneous coalesence and diapiric uprise of granites. Thus the reworking of the sialic crust at depth was concommitant with the deformation of the overlying greenstone successions, and the melts derived from anatexis of this older crust could be the local source for some of the granites intruding greenstone sequences [e.g. the Lochiel granite (Sr_o = 0.7054) in the Swaziland Supergroup, (Hunter, 1974, p.284; Glikson, 1976, p.1274)]. The upward rise of mantle-derived granites through parallel zones in the lower crust would lead to a constrictional domain with intense vertical extensions, and may account for the steep attitide of the domal structures.

Processes of reconstitution of older sialic crust to give new gneisses such as advocated in this thesis are at odds with views held by the isotope geochronologists who maintain that crustal reworking was not an important process in Archean time (Moorbath, 1975). Indeed, using arguments based on Sr^{87}/Sr^{86} ratios the arguments seem valid, even when the analyzed rocks come from areas where field evidence of reworking is apparent (cf. Moorbath and Pankhurst, 1976). The validity of low Sr_o ratios as a criterion for short crustal history of certain rock suites has recently been questioned (Pidgeon and Hopgood, 1975), and mechanisms of wholesale redistribution and homogenization of parent and daughter elements (i.e., Rb/Sr) during high grade metamorphism have been advocated (Bridgwater and Collerson, 1976). However, the Iterungnek gneisses from Labrador fit into the present model of Sr evolution quite well, having a Sr_o of 0.7064, indicating that it is not a mantle derived suite (Hurst et al., 1975).

In conclusion, it should be noted that reworking of early sialic crust has been demonstrated from Labrador (Collerson et al., 1976; this thesis), Scotland (Sutton and Watson, 1962; Dearnley, 1962; Watson, 1967; Davies, 1975), Greenland (Chadwick et al., 1974a, 1974b) and South Africa (Hunter, 1974) and is thus a world wide phenomenon in the ancient cratons. The significance of this process in the evolution of the sialic crust has yet to be evaluated and explained, but as more such areas are recognized and researched the mechanisms involved will be more appreciated. The apparent low Sr_o ratios from areas such as Greenland where the gneisses are reworked in field-demonstration indicate that the concept of initial or mantle ratios as fingerprints of "crustal residence" of granitic gneisses needs re-evaluation. The excellent exposures of northern coastal Labrador certainly have much to offer to this and other aspects of Archean crustal development. Few other such areas offer the opportunity for us to investigate geological activity in the Earth's crust at a time which is so near to "the very beginning of things".

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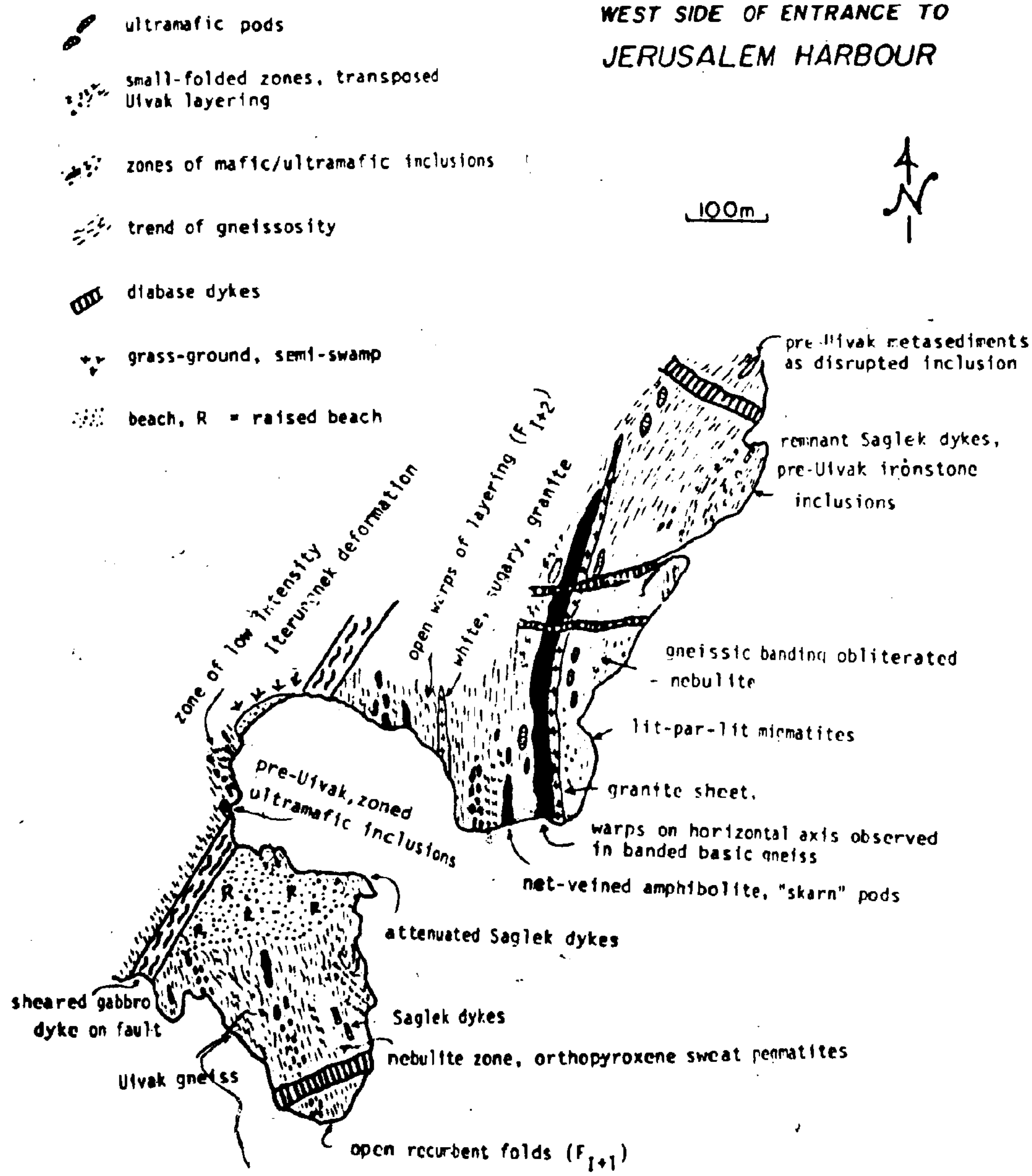
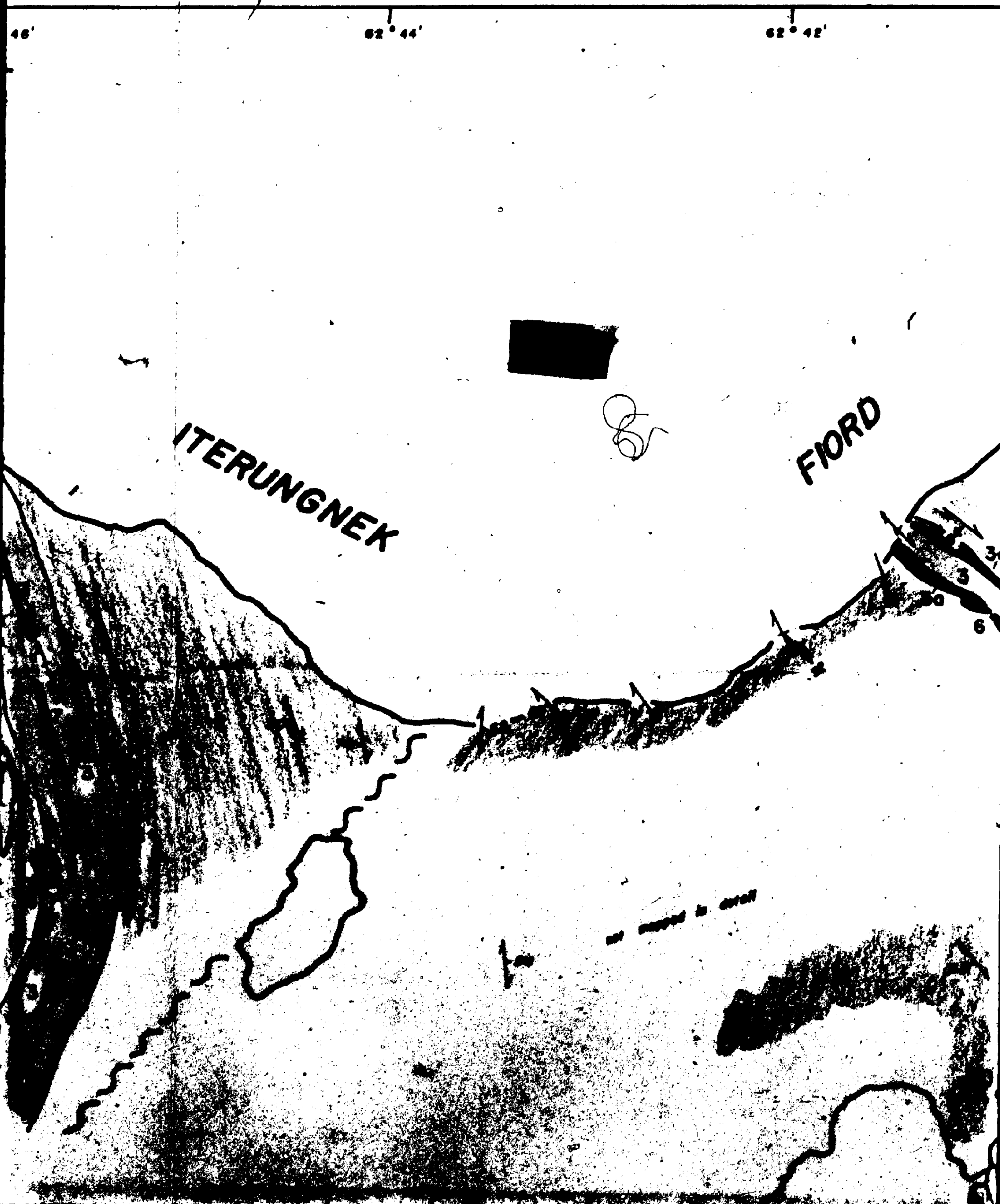
MAP 2

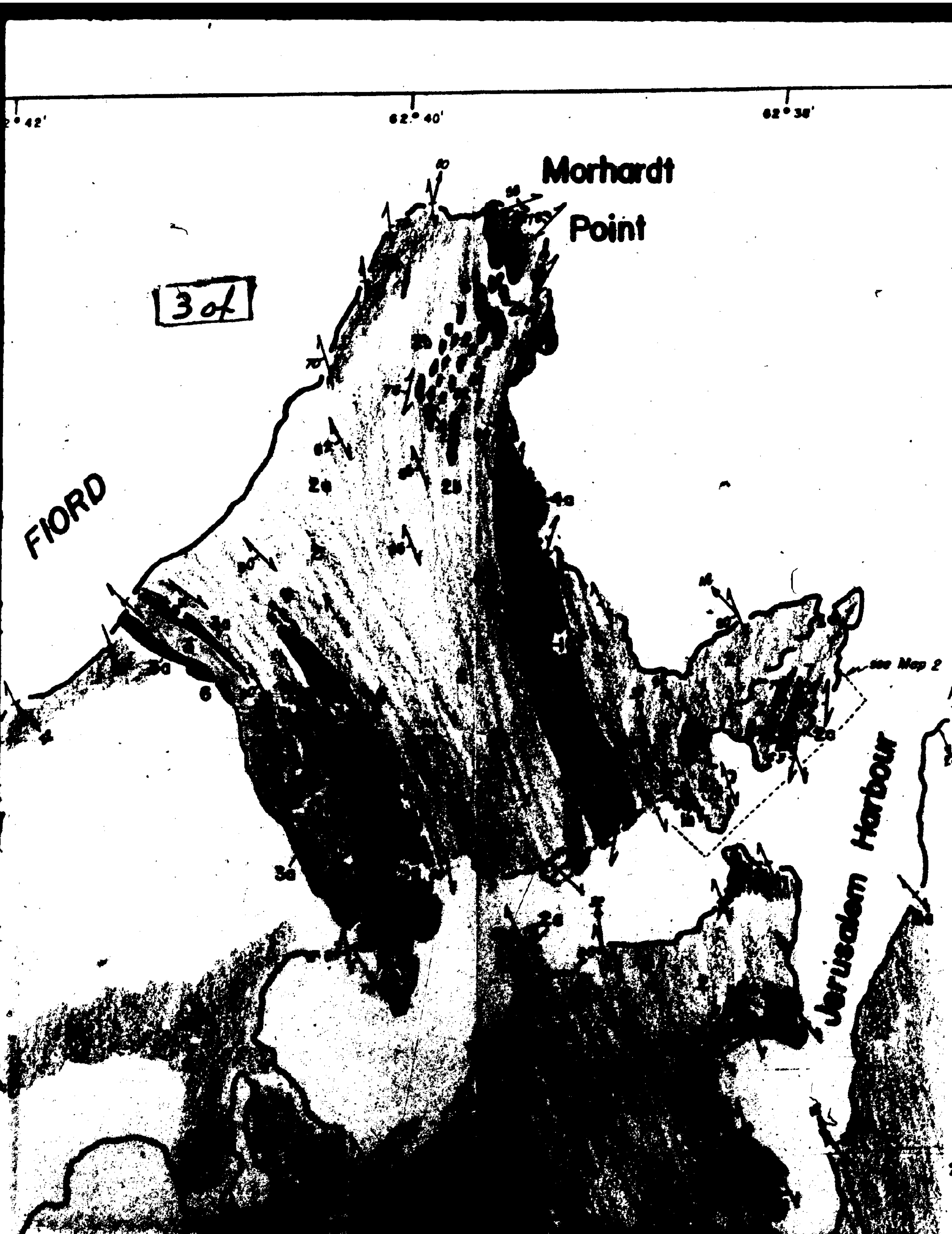
WEST SIDE OF ENTRANCE TO

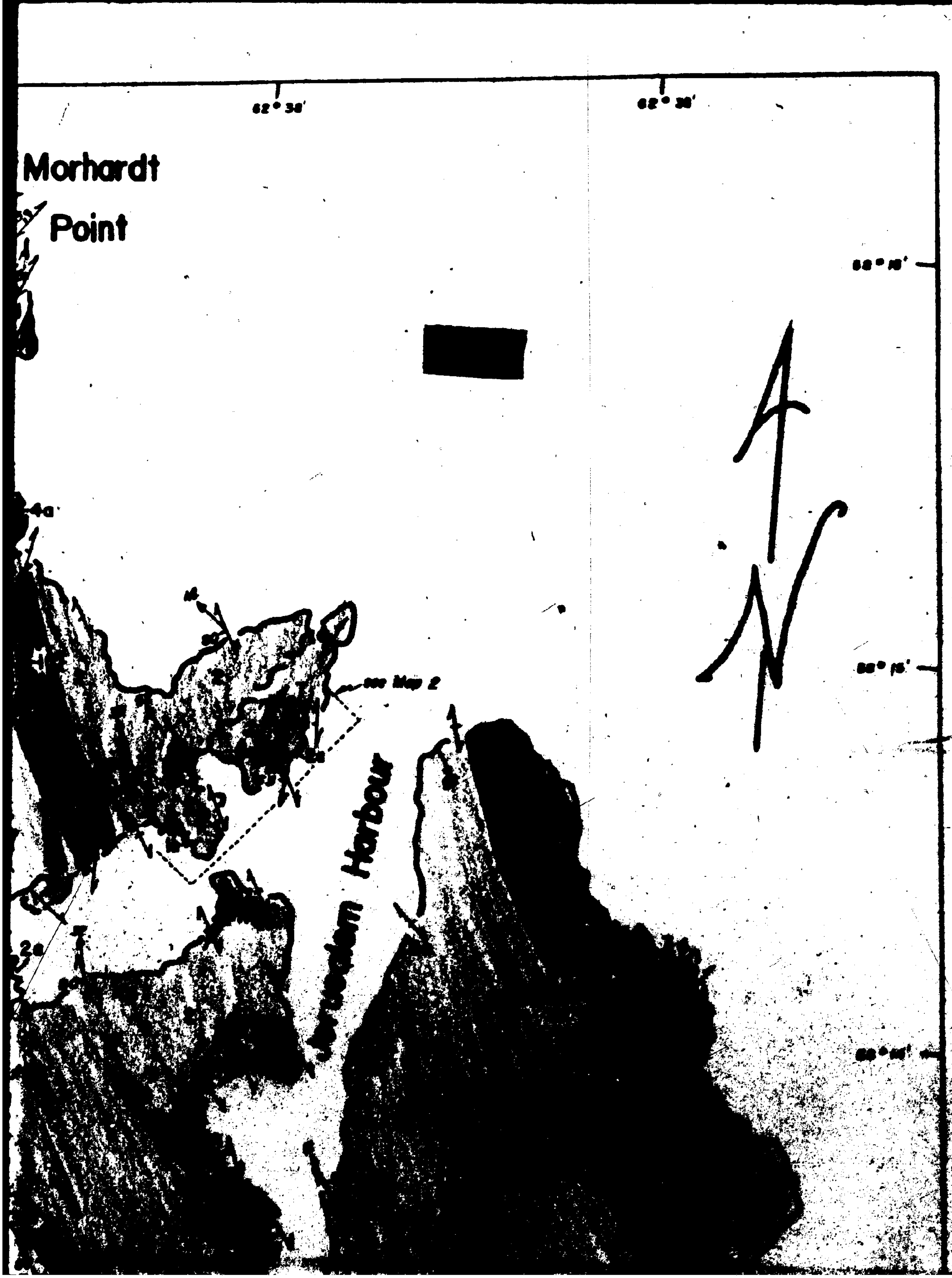
JERUSALEM HARBOUR

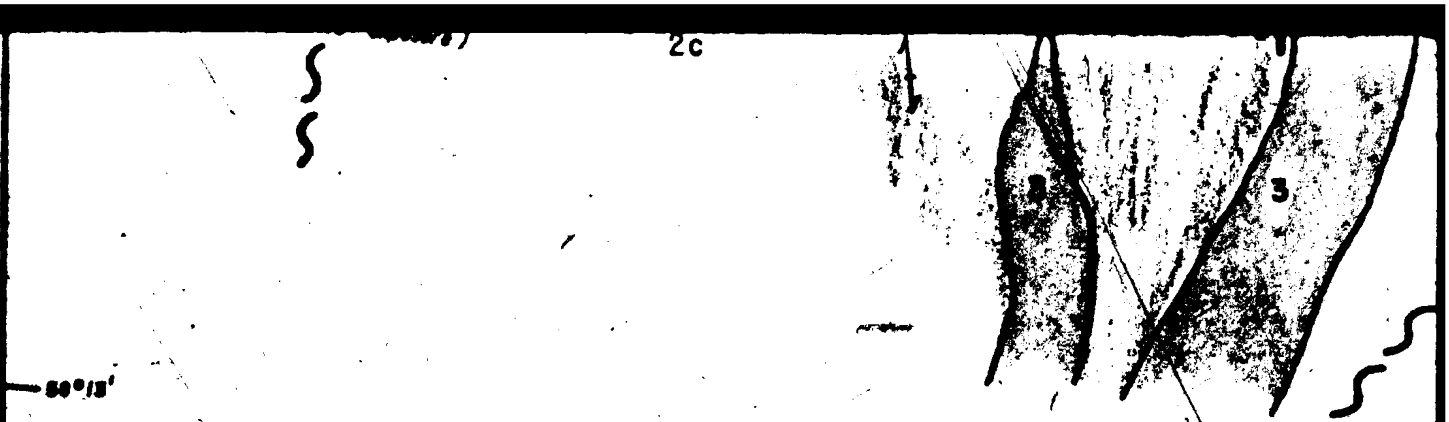


ARCHEAN GEOLOGY OF THE REGION AROUND JERUSALEM HARBOUR, LABRADOR


46'
62° 44'
62° 42'
[redacted]
ITERUNGNEK
FIORD
3
3
30
6


62° 42'
62° 40'
62° 38'
Morhardt
Point
3 of
FIORD
see Map 2
Jerusalem Harbour


Morhardt
Point
see Map 2
Harbour
4a
2a
[redacted]



LEGEND

Granitic sheets and pegmatite bodies of various ages

Ultramafic rocks

Basic gneisses of uncertain origin as isolated bodies in the quartzo-feldspathic gneisses; 6a Mafic-ultramafic layered intrusion

Basic Gneiss Belts — massive and well-banded amphibolites and pyroxolites ([illegible] character [illegible] diagrammatic); [illegible] metasediments

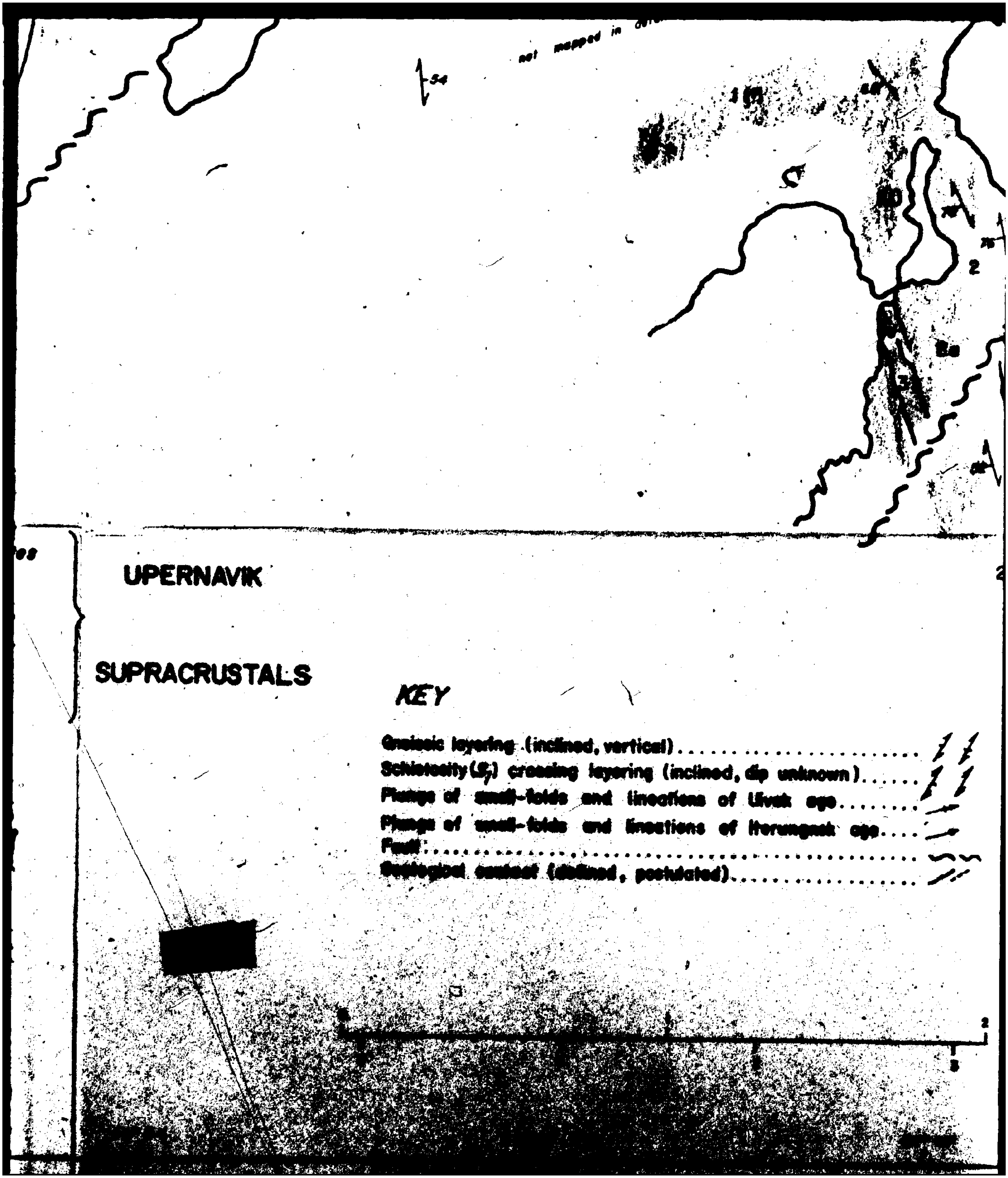
58°12'

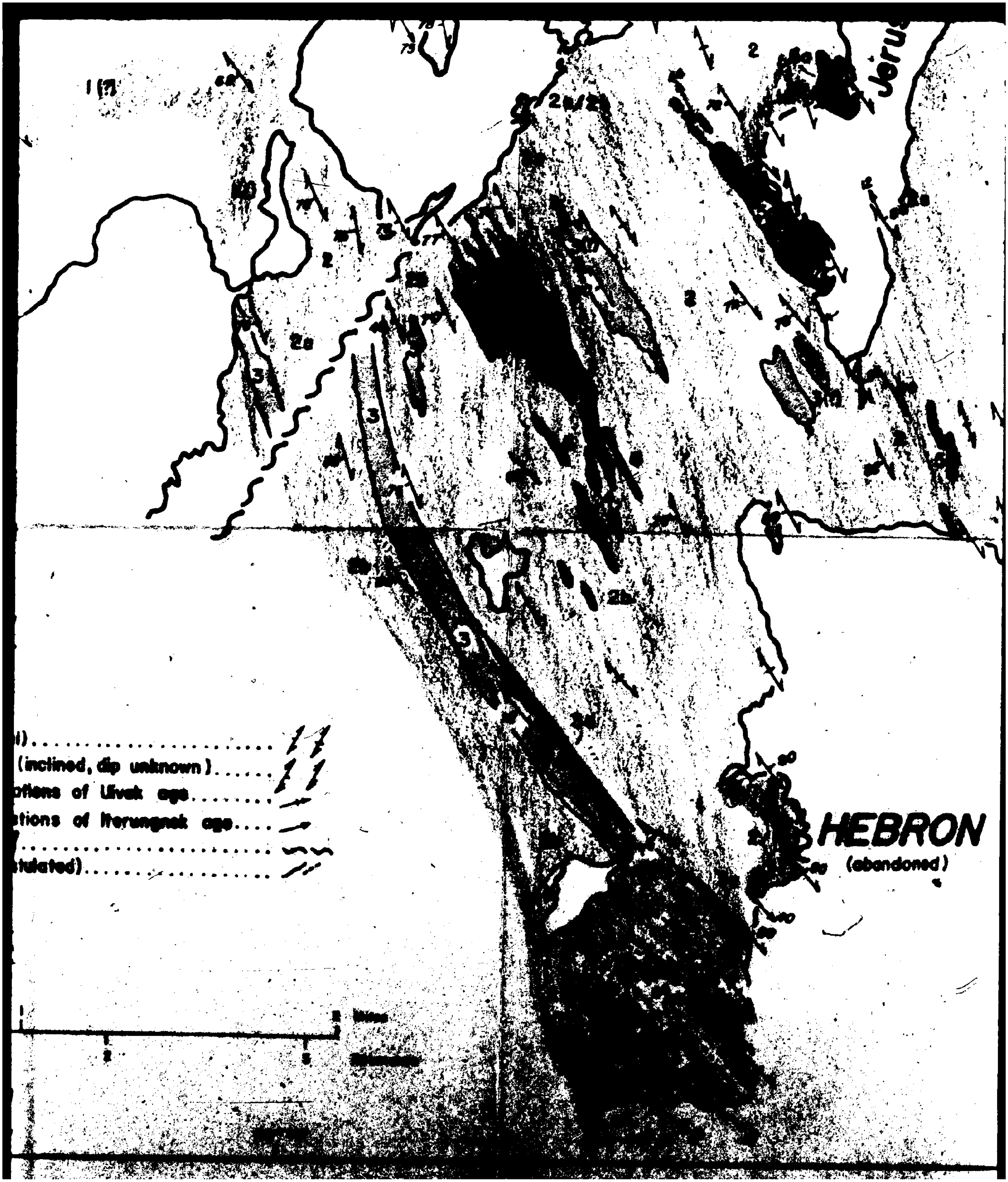
Metasedimentary Gneiss Belts -- rusty politic and semi-politic rocks with minor quartzites, marbles, and impure calc-silicates, intercalated thin basic gneiss layers; contains porphyritic meta-melagabbro sills [illegible] of [illegible] village; [illegible] Mappable basic gneiss units associated with the metasediments

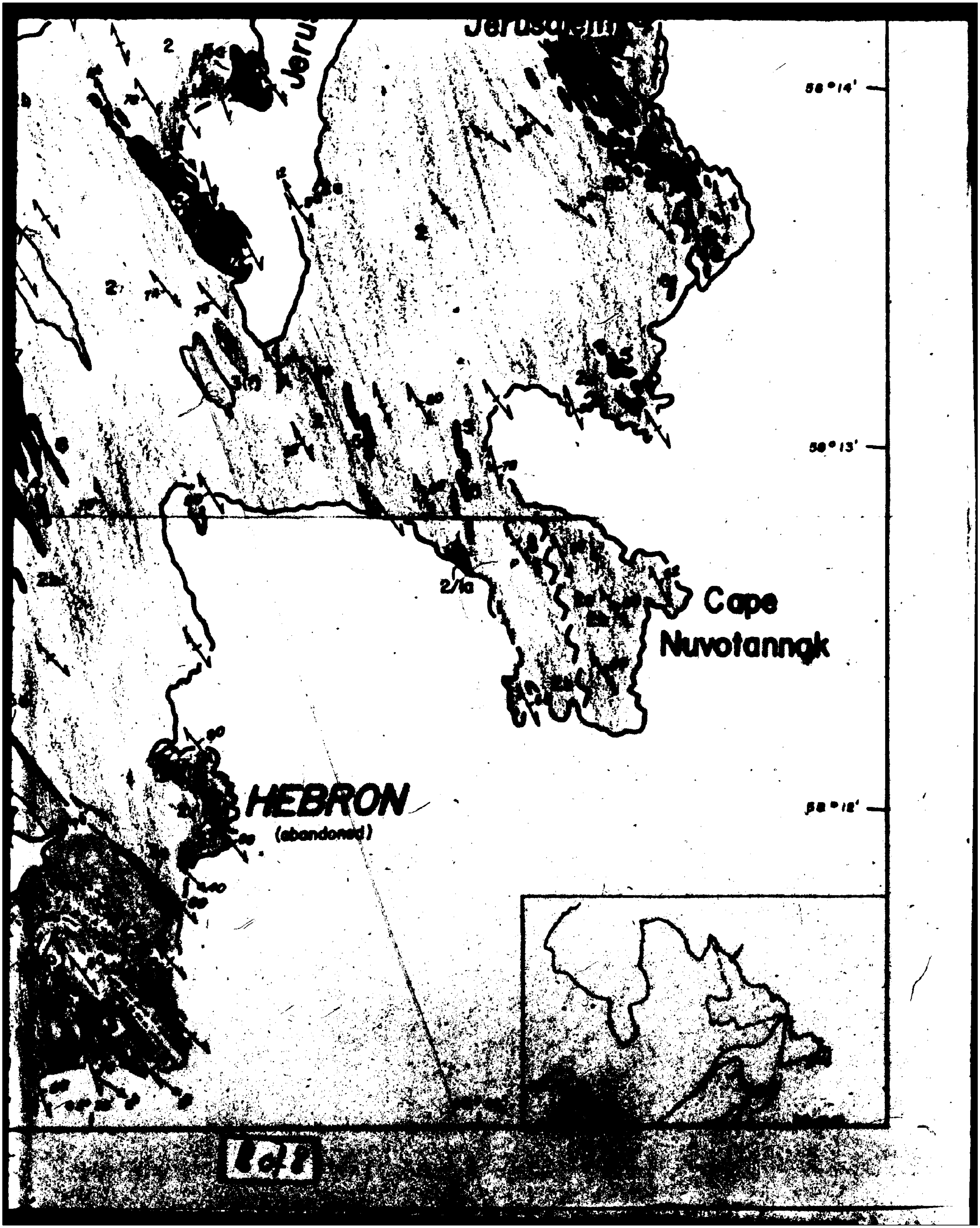
FIERUMNEK GNEISSES heterogeneous suite of foliated rocks [illegible] of [illegible] composition, derived in part by the [illegible] of the [illegible] accompanied by syntectonic [illegible] 2a [illegible] and [illegible]; 2b Weakly [illegible]; 2c Sheared and [illegible] Fault

U[illegible] [illegible] banded, tonalitic, granodioritic, and [illegible] lithologies as [illegible] banding exhibits [illegible]

58°11'


UPERNAVIK
SUPRACRUSTALS
KEY
Gneissic layering (inclined, vertical)
Schistosity crossing layering (inclined, dip unknown)
Fault
Geological contact (defined, postulated)


HEBRON
(abandoned)
(inclined, dip unknown)
of Uivak age
of Iterungnek age



Cape
Nuvotannngk
HEBRON
(abandoned)
58° 14'
58° 13'
58° 12'
2/1a
8 of 8