LATE ARCHEAN IGNEOUS, METAMORPHIC AND STRUCTURAL EVOLUTION OF THE NAIN PROVINCE AT SAGLEK BAY, LABRADOR

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LATE ARCHEAN IGNEOUS, METAMORPHIC AND STRUCTURAL EVOLUTION OF THE NAIN PROVINCE AT SAGLEK BAY, LABRADOR

by

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ABSTRACT

Field and laboratory studies of a group of Late Archean (3000-2700 Ma) gneisses formerly assigned to the "undifferentiated gneisses" of Hurst et al. (1975) provides convincing evidence for crustal reworking in the sense of Moorbath (1975).

These rocks (for which the term "Kiyuktok gneisses" is introduced) show completely gradational contacts with the 3,500 Ma old Uivak gneisses and range from recognizable derivatives of the earlier suite to structureless nebulites and, ultimately, to coarse-grained intrusive pegmatites containing garnet and orthopyroxene. Even in areas of extensive mobilization, the Kiyuktok gneisses contain remnants of Uivak gneisses and partially resorbed Saglek dykes, which is compelling evidence for derivation from the earlier rocks. The Kiyuktok gneisses are spatially and temporally associated with a group of Late Archean orthogneisses derived from sheets and dykes of tonalite and granodiorite. These are described and correlated lithologically with the Ikarut and Kammarsuit gneisses of the Hebron and Nachvak areas (Collerson, Kerr and Compston, 1980).

The petrology of Kiyuktok gneisses in various stages of development strongly suggests that they formed by progressive partial melting of the Uivak suite to produce rocks which consist of mixtures in various proportions of relict Uivak "restite" (largely plagioclase) and a Qz-Ab-Or minimum melt.

High degrees of melting led to the formation of garnet-bearing granitic (s.s.) magmas, which migrated to higher levels.

Estimates of physical conditions derived from mineral assemblages in supracrustal rocks by modern geothermometry and geobarometry techniques suggest temperatures of 750-850°C, pressures of 7-9 kb and partial H_2O pressures of 0.2-0.4. These conditions are not sufficient for extensive melting at present levels of exposure, unless substantial introduction of volatiles took place.

Accordingly, a model is presented whereby melting and reactions at deeper levels leads to dehydration and melting of Uivak gneisses and Upernavik metasediments, producing mobile H_2O-rich melts. Emplacement of pegmatites and granites at the present level of exposure introduced large quantities of water, which caused effectively instantaneous solidus depression and initiated rapid _in situ_ melting under H_2O-saturated conditions.

Late Archean intrusive rocks, such as the Ikarut and Kammarsuit gneisses, are interpreted as mixtures of "juvenile" tonalitic and trondhjemitic magma derived by partial melting of a short-lived mafic precursor and enriched granitic melts produced by reworking of the Uivak gneisses via the mechanism above.

These petrogenetic models for Late Archean crustal development are entirely consistent with isotopic evidence (Collerson, Kerr and Compston, 1980), but do not agree with the models of Moorbath (1975) and Moorbath and Pankhurst (1976) for equivalent rocks in West Greenland.

The ultimate causes of the Late Archean thermal event which caused reworking are presently obscure. It may relate to crustal subsidence caused by thickening due to overfolding and thrusting during the intercalation of basement and cover prior to 3000 Ma ago, or, alternatively, to the emplacement of mantle derived mafic liquids at the base of the crust.

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FRONTISPIECE : LOOKING NORTH FROM KIYUKTOK COVE , EARLY JULY 1978. THE FOLDED STRATA IN THE DISTANCE ARE THE PROTEROZOIC SEDIMENTS OF THE RAMAH GROUP .

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LIST OF ABBREVIATIONS

The following abbreviations for mineral species are used in places in this thesis:

Qz - Quartz
Pl - Plagioclase
K-fsp - Potassium feldspar
Opx - Orthopyroxene
Cpx - Clinopyroxene
Hb - Hornblende
Bi - Biotite
Sill - Sillimanite
Ky - Kyanite
Cd - Cordierite
Gt - Garnet
St - Staurolite
Sp - Spinel
Ep - Epidote

CHAPTER 1

INTRODUCTORY REMARKS

In the last decade, a vast amount of work has been carried out in well-exposed Archean terrains in Australia, South Africa, Canada and Greenland. As a result, some understanding of early crustal processes is now emerging. One of the most important discoveries was the recognition of very early Precambrian gneisses ($>$3,600 Ma in age) in the Godthaab area of West Greenland (McGregor, 1973; Black *et al.*, 1971; Moorbath *et al.*, 1972) and at Saglek Bay in Northern Labrador (Bridgwater *et al.*, 1975; Hurst *et al.*, 1975; Collerson *et al.*, 1976; Collerson and Compston, in prep.).

However, these early Archean enclaves are only of limited extent and most Archean rocks are between 3,000 Ma and 2,800 Ma in age (e.g. Windley, 1973, 1977). Archean terrains are divisible into high-grade and low-grade terrains (Windley and Bridgwater, 1971) and relationships between the two types are a subject of much debate amongst Precambrian earth scientists. It seems most likely that high-grade terrains represent deep levels of low-grade granite-greenstone terrains (e.g. Windley and Bridgwater, 1971; Shackleton, 1976; Glikson, 1977, 1979), although some workers have suggested that they represent a completely different environment (Windley and Smith, 1976; Bridgwater and Collerson, 1976, 1977; Young, 1978).

Whatever their relationship to the volcano-sedimentary terrains, it is beyond discussion that Archean high-grade gneiss complexes represent the best exposures of deep crustal levels and offer an opportunity to study the processes involved in the formation of early continental crust. Most of the present concepts regarding the origin and growth of the continental crust come from studies of the best-known Archean high-grade terrain, the "North Atlantic Craton" of Bridgwater et al. (1973b), which comprises Eastern Labrador, Greenland and Northwest Scotland.

Recent ideas concerning the development of crust in this area have leaned heavily upon isotopic evidence and have stressed the importance of "juvenile" sial which was added in immense quantities between 3,000 and 2,700 Ma ago (Moorbath, 1975; Moorbath and Pankhurst, 1976; Hamilton et al., 1979). The reworking of older sialic material has largely been discounted in these models. However, it has been documented isotopically in two African examples (Davies and Allsopp, 1976; Hickman, 1978), and inferred from field evidence in West Greenland (Chadwick et al., 1974; Bridgwater et al., 1974). In the Northern Labrador portion of the North Atlantic Craton, it was recognized by Hurst et al. (1975) that the little understood group of rocks termed "undifferentiated gneisses" might to some extent represent reworked 3,500 Ma old crust. It is thus of great importance to investigate potential examples of crustal reworking in order to evaluate the validity of statements such as those of Moorbath (1975) concerning the impossibility of reworking sialic crust on a "grand scale". It should be noted at this point that the term "reworking" is used in the sense of Moorbath (1975) to denote "partial or complete melting leading to mobilization and reconstitution as an essentially new rock", and does not imply "structural" reworking via recrystallization and deformation (c.f. Watson, 1973).

This thesis presents the results of detailed studies of quartzofeldspathic rocks which were formerly assigned to the "undifferentiated gneisses" of Hurst et al. (1975). The name "Kiyuktok gneisses" is introduced for these rocks and compelling evidence for their derivation by reworking of the earlier Uivak gneisses is presented. This project forms part of a broader investigation and was conducted in parallel with Rb/Sr and Pb-Pb isotopic studies by Dr. K. D. Collerson. Isotopic evidence is in full agreement with the evidence from field relations, petrology and geochemistry presented herein and is discussed fully by Collerson, Kerr and Compston (1980). These authors also discuss the petrogenesis of Late Archean intrusive rocks (Ikarut and Kammarsuit gneisses).

The field studies reported in this thesis were largely concentrated within a 10 x 10 km area centred upon Kiyuktok Cove, where critical relationships between the Uivak gneisses and the Kiyuktok gneisses are preserved. However, the Kiyuktok gneisses are of regional extent and samples from other parts of the Archean terrain (provided by K.D.C.) have also been incorporated in this study.

Chapters 3 and 4 of this report discuss the field relations and petrology of the Uivak gneisses, Kiyuktok gneisses and Late Archean intrusive rocks in some detail. These results are discussed in Chapter 5, where evidence for the operation of anatectic processes in reworking is presented. Chapter 6 describes the supracrustal rocks of the Upernavik suite, and Chapter 7 the ultramafic rocks. Chapter 8 deals with metamorphism and attempts to place constraints on physical conditions during the reworking of the Uivak gneisses. Estimates of P-T-X conditions are derived by modern techniques of geothermometry and geobarometry.

The structural development of the Archean complex is described and discussed in Chapter 9, and particular attention is paid to evidence for early crustal thickening by thrusting and nappe formation (c.f. Bridgwater _et al._, 1974; Myers, 1976).

The final chapter in this thesis attempts to integrate the previously presented evidence into (1) a model for the reworking process, and (2) an overall model for Late Archean crustal development in Northern Labrador. Some suggestions are made for further lines of investigation.

CHAPTER 2

REGIONAL GEOLOGICAL SETTING

2.1. GENERAL GEOLOGY OF NORTHERN LABRADOR

The Labrador peninsula is almost entirely underlain by crystalline rocks of Precambrian age and is readily divisible into a number of structural trends on the basis of structural trends and isotopic ages (Stockwell 1963, 1964). Two of these provinces, the Superior and Nain Provinces, are of Archean age and the other two, the Churchill and Grenville provinces, are of lower and upper Proterozoic age respectively.

Although the boundaries between these provinces have since been revised (Taylor, 1971), the nomenclature has remained in its original form. The locations and extent of the structural provinces currently recognized in Labrador are shown in Fig. 1. For reference purposes, the Precambrian time scale used in Canada (Stockwell *et al*., 1970) is shown in Fig. 2.

With respect to Fig. 1, it should be noted that the Makkovik sub-province is essentially a subdivision of the Nain Province. Its status was raised by Taylor (1971) on the basis of (1) differing structural trends to the rest of the Nain Province and (2) the presence of an extensive Proterozoic cover sequence (the Aillik Group) overlying the Archean. Taylor's modifications are generally accepted by workers in the area, but there has been some discussion of their validity (Douglas, 1972).

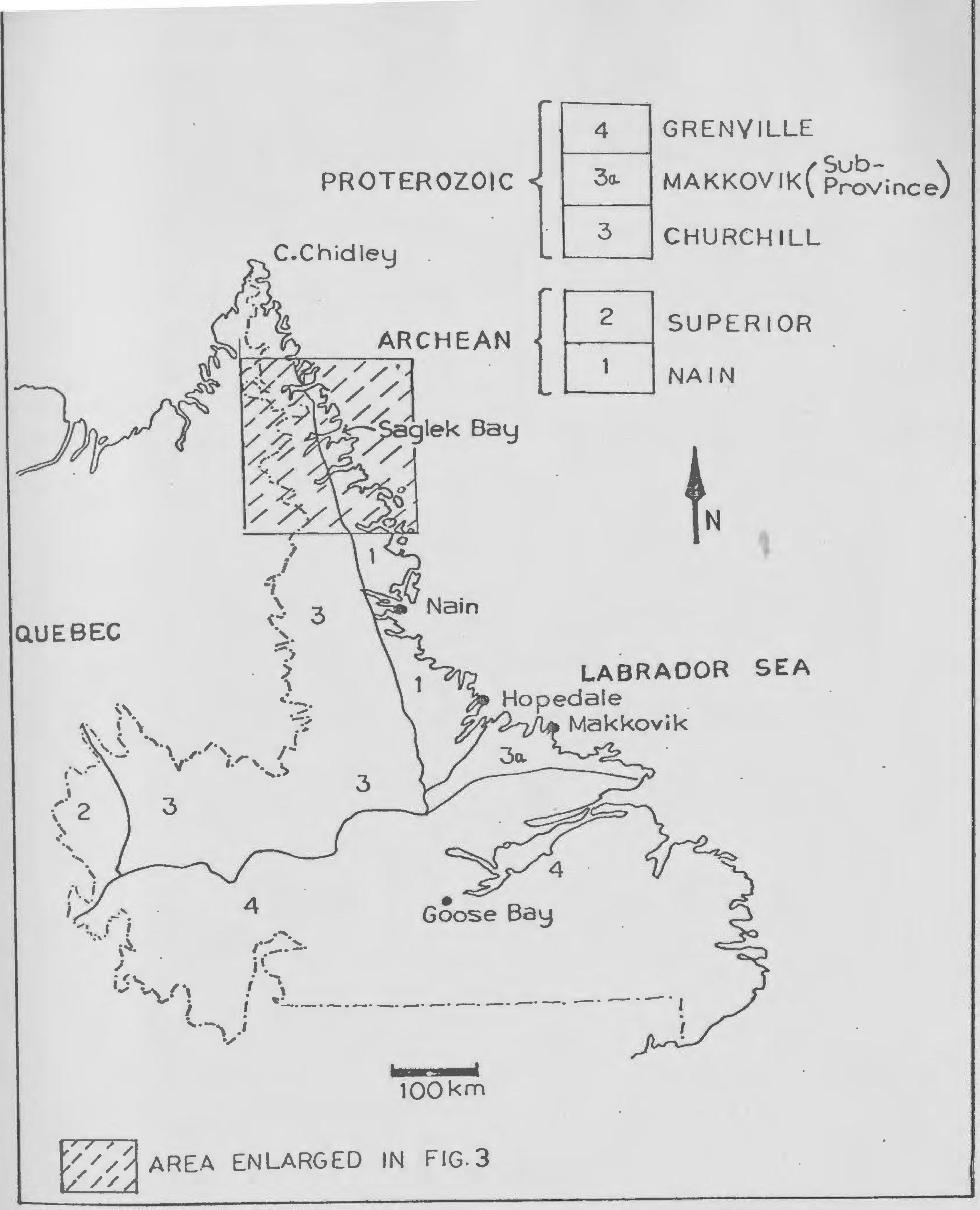


Figure 1 . Structural Provinces in Labrador . After Stockwell(1964) and Taylor(1971)

EON	ERA	SUB-ERA	CLOSING OROGENY	REPRESENTED IN LABRADOR BY :
PROTEROZOIC	HADRYNIAN			
			GRENVILLIAN [955]*	GRENVILLE PROVINCE
	HELIKIAN	NEOHELIKIAN		
			ELSONIAN [1370]*	ANORTHOSITE - ADAMELLITE SUITE
		PALEOHELIKIAN		
			HUDSONIAN [1735]*	CHURCHILL PROVINCE
	APHEBIAN			
			KENORAN [2480]*	NAIN AND SUPERIOR PROVINCES
ARCHEAN				

*MEAN K-Ar AGE IN Ma

Figure 2 . Precambrian Time Scale in common use in the Canadian Shield (After Stockwell _et al_., 1970)

With respect to Fig. 2, it should be noted that the radiometric ages are K-Ar ages and therefore represent periods of post-orogenic cooling and uplift in the various provinces, rather than the absolute ages of the component rocks. It should also be noted that the "Elsonian orogeny", which applies specifically to Labrador, probably reflects widespread re-setting of K-Ar ages during the intrusion of an extensive suite of anorthositic, monzonitic and granitic plutons between 1500 and 1300 Ma ago. It is therefore a magmatic and thermal event, and was not associated with any large-scale folding and metamorphism.

As this thesis is concerned with the evolution of Archean rocks in northern Labrador, only the northernmost portions of the Churchill and Nain Provinces are discussed in detail. For a more general overview of the geology of Labrador, the reader is referred to Greene (1974).

A simplified geological map of a portion of northern Labrador centred upon the thesis area is shown in Fig. 3. The area is bisected from north to south by a major geological boundary which separates the Churchill and Nain Provinces. This boundary is marked by a zone of very high strain containing abundant mylonites and pseudotachylites.

Within the Nain Province, the oldest rocks are the polydeformed amphibolite and granulite facies gneisses of the Archean complex (Unit 1). These are the subject of this

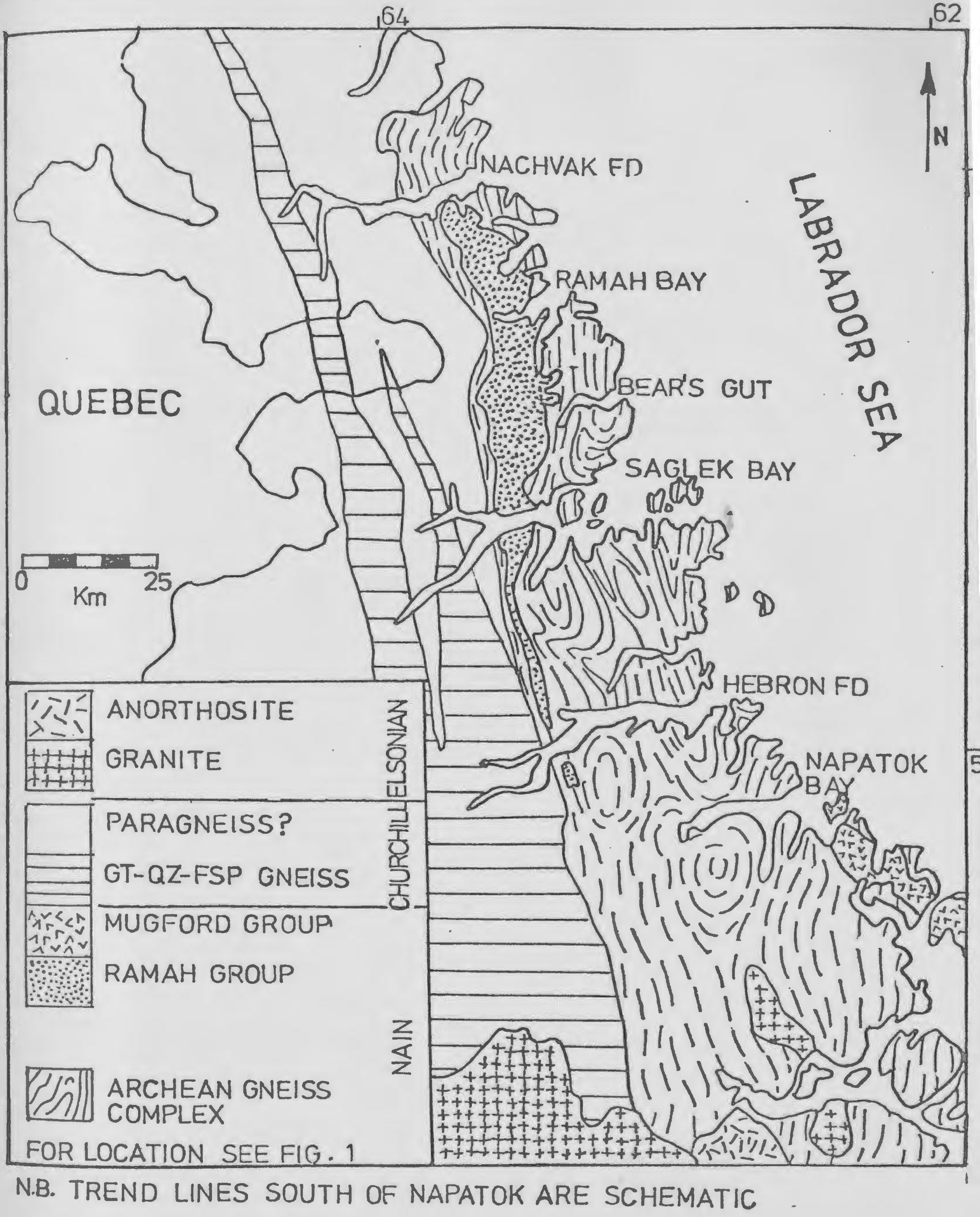


Figure 3 . Geology of Northern Labrador . Taken from Greene(1972) , with modifications after Morgan(1975) .

thesis and will be described in detail in a later section.

The Archean gneisses are overlain by two supracrustal sequences of Early Proterozoic age known as the Ramah Group and the Mugford Group (Daly, 1902). The Ramah Group (Unit 2) is described by Morgan (1975) and consists of almost 2000 m of quartzites, greywackes and limestones, with minor volcanic rocks. The Mugford Group (Unit 3) is composed of mafic volcanic and pyroclastic rocks, with intercalated sedimentary rocks at the base of the sequence (Taylor, 1971; 1972; Barton, 1975). Both sequences are considered to be of Aphebian age and were recently correlated with each other by Smyth _et al_. (1978).

The Ramah Group is affected by Hudsonian deformation and metamorphism in the west, but is unmetamorphosed in the east, although a strong penetrative cleavage is developed. The Mugford Group was apparently outside the area affected by Hudsonian events and is flat lying and unmetamorphosed.

The northern part of the Churchill Province is underlain by a variety of high grade metamorphic rocks (Units 4 and 5) which yield ages between 1800 and 1600 Ma (Wanless, 1969). Field evidence (Taylor, 1970; Morgan, 1975) suggests that many of these gneisses are reworked equivalents of the rocks within the Archean complex.

The last major event in the geological evolution of Northern Labrador was the anorogenic intrusion of a suite of anorthositic, monzonitic and granitic intrusions between 1500 Ma and 1300 Ma ago (see, for example, Emslie, 1978). The northern extremity of this Elsonian magmatic province is represented in Fig. 3 by Units 6 and 7.

2.2. EARLY WORK WITHIN THE ARCHEAN COMPLEX

The history of geological investigation in northern Labrador can be traced back to 1811, when two missionaries noted the existence of gneisses and slates whilst on an overland trek from Okak to Ungava Bay. This, and a number of other early investigations, are reviewed by Morgan (1975) and Ryan (1977) and will not be discussed here.

For our purposes, the first significant investigation was that of Kranck (1939a) who considered the grey gneisses of northern Labrador to represent extensively granitised sediments. Similar opinions regarding the origin of the coastal gneisses were subsequently expressed by Tanner (1944) and also by Christie (1952) and Douglas (1953), both of whom carried out some coastal mapping.

The first regional mapping program in the area was conducted by the Geological Survey of Canada during the summers of 1968 and 1969. The results of this investigation are summarized by Taylor (1970), who describes the Archean as "migmatite, granulite and amphibolite" and also notes the existence of meta-sedimentary rocks and small ultramafic bodies. As a result of this reconnaissance mapping, the position of the boundary between the Churchill and Nain provinces was changed considerably (Taylor, 1971).

The field seasons of 1971 and 1972 saw the first attempts at detailed mapping in northern Labrador. The results of this helicopter-supported investigation of the basement rocks and Ramah Group between Nachvak Fiord and Saglek Fiord are summarized by Morgan (1975). A number of rock types were distinguished within the Archean complex, including acid gneiss, migmatite, agmatite, amphibolite, augen gneiss, paragneiss and a variety of ultramafic rocks. It did not prove possible to establish any chronological relationships between the various rock type, but the possibility of doing so in the future was noted.

2.3. THE GREENLAND CONNECTION

The possible correspondence of geological events in West Greenland and coastal Labrador was first noted by Kranck (1939a, b), who was impressed by the similarity of the rocks.

More recently Bridgwater et al. (1973a) compared structural provinces in Greenland and Eastern Canada and found many similarities in the geological evolution of the two regions. A natural consequence of this work was the definition of a "North Atlantic" Archean craton by Bridgwater et al. (1973b). This is shown in Fig. 4 and includes the Nain Province, the Central Archean block of Greenland and the Scourian rocks of north-west Scotland.

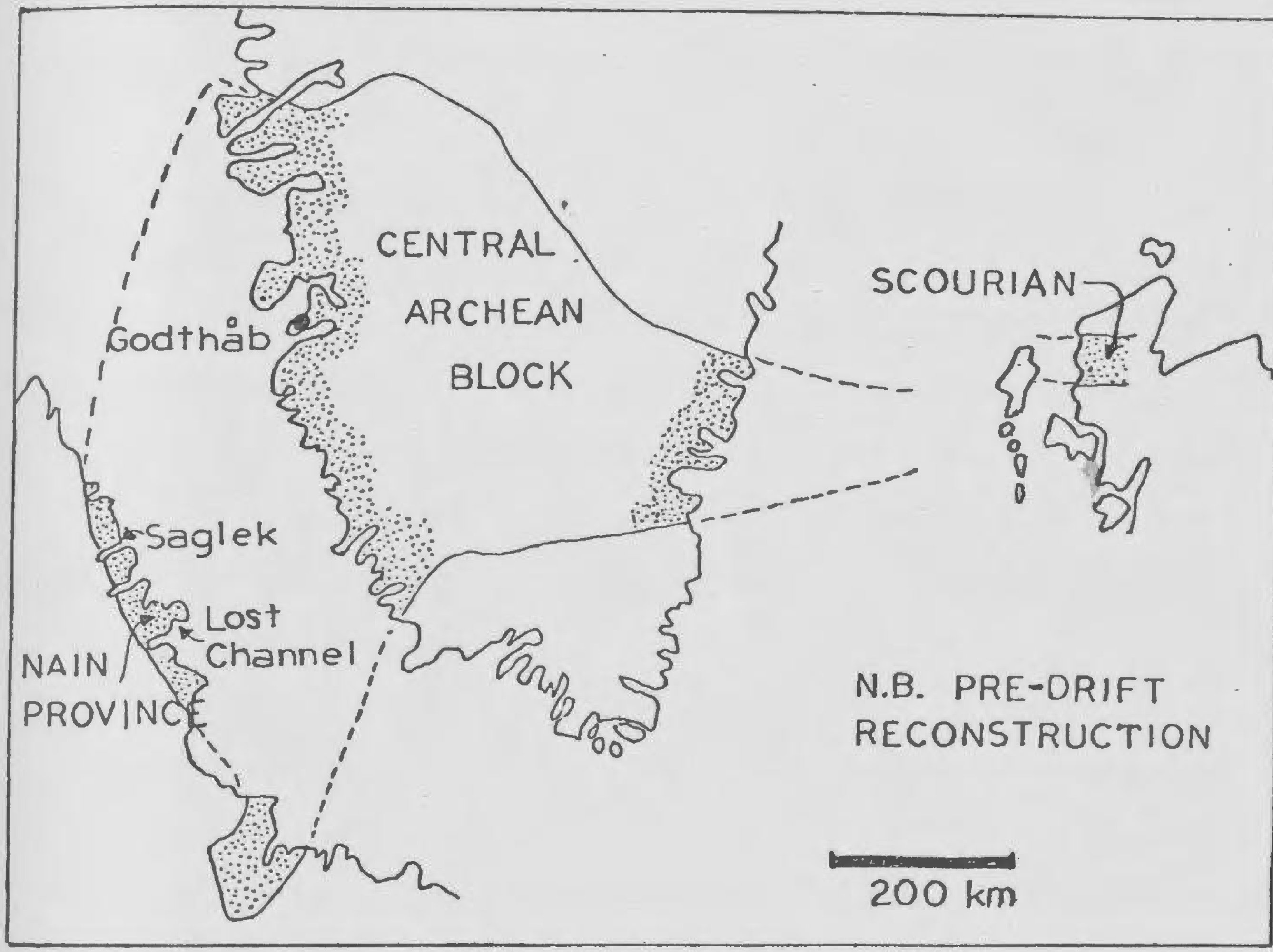


Figure 4 . The Distribution of Archean Rocks in Eastern Labrador , Greenland and North-west Scotland which define the North Atlantic Archean Craton . After Bridgwater <u>et al</u>.,1973b .

Field investigations in the Godthaab district of West Greenland between 1963 and 1971 culminated in the establishment of an evolutionary chronology for this segment of the Archean Craton (McGregor, 1973). The erection of this chronology relied heavily upon the use of one particular "time marker" -- a suite of discordant amphibolite inclusions believed to represent the remnants of a diabase dyke swarm (the Ameralik dykes).

Using this criterion, McGregor (1973) divided the rocks within the Archean complex into two groups: (1) lithologies which pre-date the emplacement of the Ameralik dykes and (2) lithologies which were formed or reworked after the intrusion of the dykes.

Pre-dyke events involved the development of a quartzofeldspathic gneiss complex via the metamorphism and intense deformation of a composite suite of intrusive rocks of dioritic to granitic composition. These early gneisses locally contain inclusions of even earlier supracrustal rocks and are identified by the presence of Ameralik dykes, which locally display discordant contacts with their host rocks.

Other groups of rocks within the Archean Complex are not seen to contain the diagnostic amphibolites and are regarded as post-dating the emplacement of the dykes. These younger rocks include both quartzofeldspathic gneisses and supracrustal rocks.

Geochronological work conducted concurrently with the field work of McGregor (1973) demonstrated that the Godthaab district contains some of the oldest terrestrial rocks which are at least 3620 Ma old by Rb-Sr and Pb-Pb methods (Black et al., 1971; $\lambda^{Rb} = 1.39 \times 10^{-11}$). Recent work (Collerson and Compston, in prep.) suggests that Rb-Sr systems in Early Archean gneisses have been partially re-set by later events and some revision of these ages may be necessary in the future. Subsequent geochronological work (Moorbath et al., 1972; Pankhurst et al., 1973) verified the field chronology established by McGregor.

Field work conducted by Bridgwater et al. (1975) in the vicinity of Saglek Bay, northern Labrador, demonstrated that events in this part of the Nain Province were broadly comparable to those described by McGregor in the Godthaab district. Hurst (1974) suggested that the Nain Province was of a similar age to the Greenland Archean with a U-Pb age of 3,400 Ma for gneisses at Lost Channel, about 100 km south of Saglek (see Fig. 4). Hurst et al. (1975) subsequently reported Rb-Sr ages from the Saglek area which are closely comparable to those from West Greenland.

Since that time, the Archean rocks in West Greenland have been subjected to intense studies by workers from the Geological Survey of Greenland (G.G.U.), Exeter University and other institutions. The Nain Province Archean in the Saglek area has received continued attention from the Geological

Survey of Canada (G.S.C.) and Memorial University of Newfoundland (see, for example, Hurst et al., 1975; Bridgwater and Collerson, 1976; Collerson et al., 1976; Jesseau, 1976; Collerson and Bridgwater, 1979). This field work has allowed the establishment of a detailed evolutionary chronology (see Table 1).

2.4. GEOLOGICAL HISTORY IN WEST GREENLAND AND NORTHERN LABRADOR

In both Greenland and Labrador, the oldest extensive group of rocks is a suite of migmatitic quartzofeldspathic gneisses of tonalitic to granitic composition. These are interpreted as metamorphic derivatives of a composite intrusive suite emplaced into the crust sometime before 3,600 Ma ago. Locally, these gneisses contain inclusions of amphibolites and metasediments which are believed to represent remnants of even earlier supracrustal rocks. These are known as the Akilia assemblage in Greenland (McGregor and Mason, 1977) and the Nulliak assemblage in Northern Labrador (Collerson and Bridgwater, 1979). Their host rocks are known as the Amitsoq gneisses (McGregor, 1973) or the Uivak gneisses (Bridgwater et al., 1975).

Both the Amitsoq gneisses and the Uivak gneisses contain the diagnostic amphibolite inclusions, which are known as the Ameralik dykes or the Saglek dykes.

Interleaved concordantly with these early gneisses, and retaining no original contacts with them, are supracrustal rocks dominated by pelitic metasediments and amphibolites of

TABLE 1: ARCHEAN GEOLOGICAL HISTORY IN GREENLAND AND LABRADOR

	LABRADOR (SAGLEK-HEBRON)	WEST GREENLAND
15.	INJECTION OF DIABASE DYKE SWARMS (2,300 ± 300 Ma)	INJECTION OF DIABASE DYKE SWARMS (2,300 ± 300 Ma)
14.	WIDESPREAD INJECTION OF LATE TO POST TECTONIC GRANITES IN SHEAR ZONES. RETROGRESSION OF HIGH GRADE ROCKS (2,800 - 2,500 Ma)	WIDESPREAD INJECTION OF LATE TO POST TECTONIC GRANITES. RETROGRESSION AND MIGMATISATION (2,700-2,500 Ma)
13.	HIGH GRADE METAMORPHISM (APPROX. 2,800 Ma)	HIGH GRADE METAMORPHISM (APPROX. 2,800 Ma)
12.	MAJOR PERIODS OF FOLDING	MAJOR PERIODS OF FOLDING
11.	REMOBILISATION OF THE UIVAK GNEISSES TO FORM THE KIYUKTOK GNEISSES. INJECTION OF TONALITES ($>$ 2,800 $<$ 3,100 Ma)	INJECTION OF NUK CALC-ALKALINE SUITE AT GODTHAAB. POSSIBLE REMOBILISATION OF EARLY GNEISSES (3,040 Ma)
10.	INTERCALATION OF UPERNAVIK SUPRACRUSTALS WITH UIVAK GNEISSES, PROBABLY BY THRUSTING.	INTERCALATION OF MALENE SUPRACRUSTALS, ANORTHOSITES AND AMITSOQ GNEISSES, PROBABLY BY THRUSTING.
9.	POSSIBLE EMPLACEMENT OF CALCIC ANORTHOSITES SOUTH OF SAGLEK.	EMPLACEMENT OF CALCIC ANORTHOSITES.
8.	DEPOSITION AND EXTRUSION OF UPERNAVIK SUPRACRUSTALS	DEPOSITION AND EXTRUSION OF MALENE SUPRACRUSTALS.
7.	INJECTION OF SAGLEK DYKES	INJECTION OF AMERALIK DYKES
6.	DEFORMATION AND METAMORPHISM	DEFORMATION AND METAMORPHISM TO PRODUCE AMITSOQ GREY GNEISSES AND BANDED GNEISSES.
5.	INTRUSION OF MEGACRYSTIC GRANODIORITES AND ADAMELLITES (UIVAK II PROTOLITH)	
4.	DEFORMATION AND METAMORPHISM PRODUCTION OF BANDED UIVAK I GNEISSES (3,700-3,600 Ma)	INTRUSION OF AMITSOQ GNEISS PROTOLITHS (3,800-3,600 Ma)
3.	INTRUSION OF UIVAK I PROTOLITH	
2.	DEPOSITION AND/OR EXTRUSION OF PRE-UIVAK SUPRACRUSTALS.	DEPOSITION AND EXTRUSION OF THE ISUA SUPRACRUSTALS.
1.	EARLY SIALIC BASEMENT?????	EARLY SIALIC BASEMENT?????

broadly "mafic" composition. Ameralik or Saglek dykes have not been seen to cut these rocks and they are thus regarded as representing a younger cover sequence possibly deposited upon the early quartzofeldspathic basement. These supracrustal assemblages are known as the Malene supracrustals in Greenland and the Upernavik supracrustals in Northern Labrador.

A second group of quartzofeldspathic gneisses, the Nuk gneisses, which do not contain Ameralik dykes, have been recognized in West Greenland. These rocks are seen to be derived by the intense deformation and metamorphism of a composite intrusive suite (McGregor, 1973; Bridgwater et al., 1975; Myers, 1978). In areas where their "intrusive" character is well preserved, tonalites, granodiorites and granites regarded as parental to the Nuk gneisses are seen to intrude both the Amitsoq gneisses and the Malene supracrustals.

In Northern Labrador, quartzofeldspathic gneisses which occupy a similar position in the chronology appear to have been derived largely by the in situ remobilization of the Uivak gneisses. These reworked rocks are designated herein as the Kiyuktok gneisses and will be discussed in detail in later sections of this thesis. Rocks similar to the typical Nuk assemblages have been recognized in the Hebron area and are known as the Ikarut gneisses (Collerson, Kerr and Compston, 1980). The Nuk gneisses have been dated at 3,040 ± 50 Ma (Pankhurst et al., 1973) but the Ikarut gneisses are somewhat younger (2,800 Ma; Collerson et al., 1980) and closely comparable in age to the Kiyuktok gneisses.

The above events took place over a period of at least 800 Ma in both complexes and involved an undetermined number of metamorphic and deformational episodes (see Chapter 9). Megascopic structures and metamorphic assemblages produced by the earliest events are only rarely preserved and the regional structural patterns in both Greenland and Labrador are largely products of Late Archean events. A few small enclaves appear to have escaped the effects of later deformation and provide most of the information concerning the early history of the complexes. The regional structural pattern is a product of the superposition of several generations of late Archean megascopic folds, which caused the development of complex 3-dimensional interference structures.

Metamorphic mineral assemblages in the rocks belong to the upper amphibolite and granulite facies and their development appears to be a late feature which was perhaps contemporaneous with the emplacement of the Late Archean quartzofeldspathic gneisses. Mineral ages from West Greenland (Black et al. 1973) suggest that granulite facies metamorphism took place about 2,800 Ma ago.

The period between 2,800 and 2,200 Ma ago was a time of stabilisation in both complexes and is represented by post-tectonic granites (the Qorqut granite in Greenland and the Igukshuak suite in Labrador) and several swarms of diabase dykes. The dykes are probably equivalent to the Scourie dykes of Scotland which were emplaced circa. 2,390 Ma ago (Chapman 1979).

The intrusion of the dykes was accompanied by extensive block faulting which exposes a number of different crustal levels. The high grade Arçhean rocks are locally retrogressed near these fault zones, many of which were active into Proterozoic times. Some of these faults may also have suffered movement during the opening of the Labrador Sea during the Mesozoic.

Table 1 (after Hurst et al., 1975 and Collerson and Bridgwater, 1979) lists the major events recognized in the evolution of the Archean complexes in Greenland and Labrador. With respect to Table 1, it should be noted that Early Archean anorthosites have not yet been unequivocally recognized in Labrador.

2.5. THE PRESENT STUDY AREA

A five year field program conducted in Northern Labrador by Dr. K. D. Collerson and several associates has so far resulted in comprehensive mapping of an area between Saglek Bay and Hebron Fiord (Fig. 5).

The area is split into two halves by a major fault zone running approximately north-south from St. John's Harbour to Hebron Fiord. This is termed the Handy fault zone and separates an area of amphibolite facies rocks to the east from a granulite facies terrain to the west.

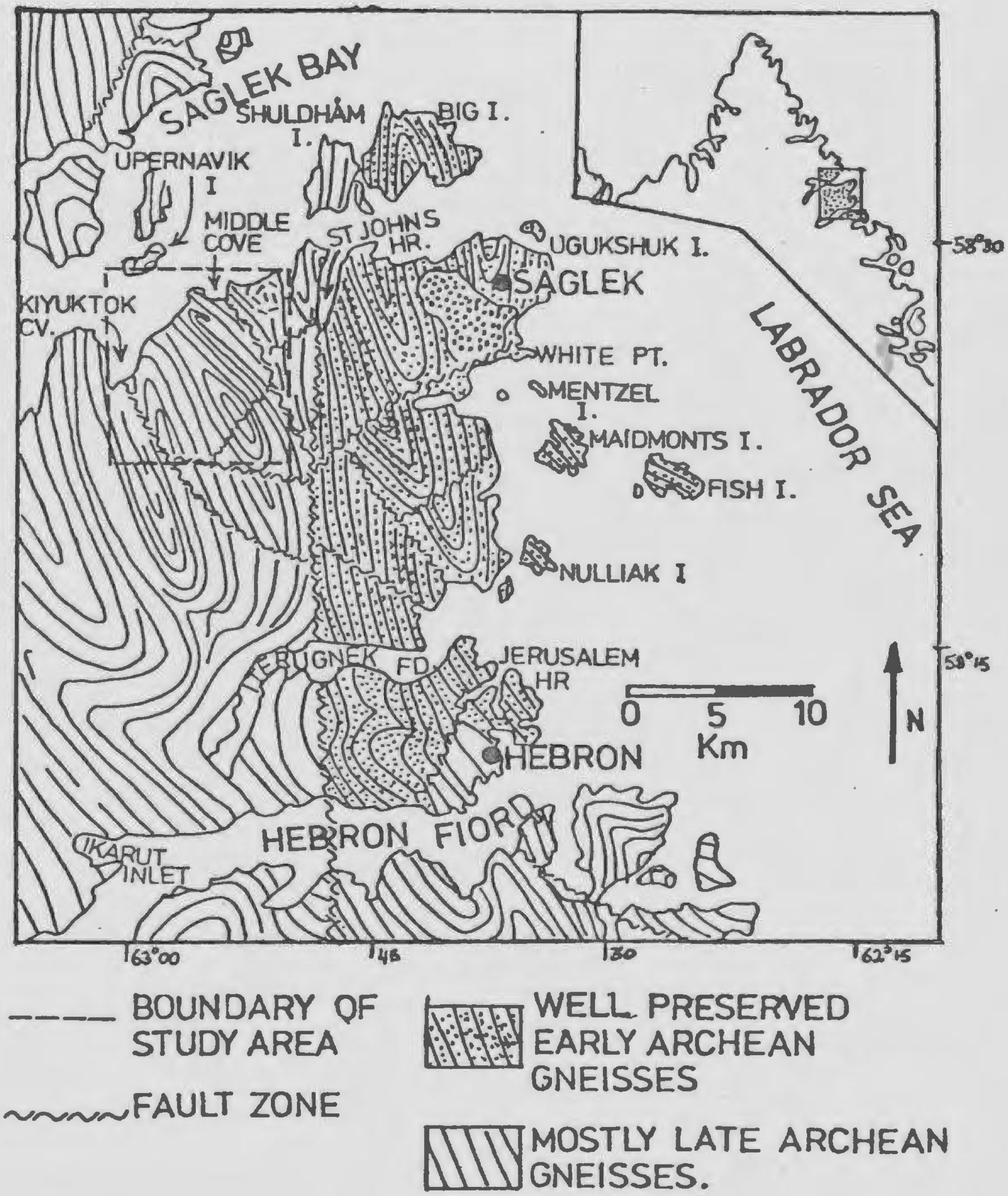


Figure 5 . Location Map for the Saglek-Hebron area of Northern Labrador .

Most of the field work has been concentrated in the eastern block, where most of the evidence relating to the early history of the complex is preserved. The western granulite facies block is not as well known and suffered extensive deformation, metamorphism and remobilisation during late Archean events. It is thus an ideal area in which to examine the igneous, metamorphic and deformational events which mark a very controversial period of earth history.

Consequently, a small area (shown in Fig. 5) was selected for a detailed investigation. It was especially well suited to this study for a number of reasons.

Firstly, it was in this area that the Kiyuktok gneisses (which were then known informally as the "blebby" gneisses) were initially recognized and they were known to be well exposed at Kiyuktok Cove, Fire Cove and Middle Cove.

Secondly, cursory examination of air photographs had shown the existence of complex megascopic interference structures within the study area, which suggested the possibility of developing some form of structural chronology. Such a chronology might then be extrapolated to other parts of the Archean complex.

For purely logistical reasons, the study area was ideal because it was relatively close to a base camp at St. John's harbour, which was used as a centre during part of the field work.

The geology of the study area is shown upon the map which accompanies this report. The area is bisected from north to south by a major fault zone running from Middle Cove to Bracelet Lake. This is known as the Middle Cove fault zone and it separates an area of well-preserved Uivak gneisses to the east from an extensively reworked area to the west. Supracrustal rocks (mostly pelites and amphbolites) are present in both eastern and western blocks but are particularly prominent in areas around Fire Cove, Kiyuktok Cove and Heart Lake. A number of complex fold structures of varied ages are outlined by supracrustal rocks in the western block. These are discussed in Chapter 9.

Structures within the eastern block are less easily defined. Over much of this part of the area, agmatites have formed via the disruption of the gneisses by late, syn-tectonic granitic material and the early features of the rocks are difficult to see. Ultramafic rocks are widely distributed throughout the area in the form of small, lensoid bodies associated with supracrustal rocks.

2.6. CLIMATE, TOPOGRAPHY, CONDITIONS AND METHODS

Northern Labrador is justly noted for rather unfriendly weather during its short summer and many days are lost to fog, wind and rain. In the 1977 field season, only 22 days of work were accomplished by the author in a period of six weeks in the field. Consequently, it was only possible to conduct a cursory examination of the study area at that time. The 1978 field season was substantially better and very few working days were lost due to inclement weather.

The topography of the study area is extremely rugged and is dominated by rocky hills of up to 500 to 600 m elevation. Broad, glacial valleys cut through these hills and provide the easiest routes for travel.

Exposure is variable; on the coastline it is superb, due to an annual cleaning and polishing which is administered by the winter ice. Inland, the outcrop is excellent in the mountainous areas but the subtler features of the rocks are obscured by an extensive lichen crust. Within the glacial valleys, outcrop is poor to non-existent and mapping is very difficult. Most of the detailed observations of the quartzo-feldspathic gneisses were made in coastal areas.

Access to Northern Labrador is also rather difficult. The geological field parties of which the author was a member gained access via a chartered Queenair aircraft of Labrador Airways which deposited us at Saglek airstrip. Transport to St. John's harbour base camp was accomplished with inflatable zodiac boats, which were subsequently used for geological investigations on the coast. Fly camps were set up by boat or on foot to serve as a base for traverses in inland areas.

Mapping was carried out on air photographs of 1:50,000 and 1:25,000 scale with plastic overlays.

CHAPTER 3

QUARTZOFELDSPATHIC GNEISSES -- FIELD RELATIONS

3.1. INTRODUCTION

Quartzofeldspathic gneisses underlie approximately 70-80% of the study area. They are divisible into two main groups on the basis of lithological characteristics and field relations. The first group are the Uivak gneisses of Bridgwater *et al*. (1975), which are distinguished from a younger group of gneisses (the Kiyuktok gneisses) by the presence of rare discordant amphibolites (Saglek dykes) representing the remnants of a diabase dyke swarm. In certain small enclaves of relatively weak deformation, the Uivak gneisses retain features which suggest that they were derived from plutonic igneous rocks of dioritic to granitic composition.

Hurst *et al*. (1975) and Bridgwater and Collerson (1976) recognized that it was possible to divide the Uivak gneisses into two sub-groups on the basis of both lithology and geochemistry; these were subsequently termed the Uivak I and Uivak II sub-groups (Collerson *et al*., 1976). The Uivak I gneisses are compositionally layered rocks of "migmatitic" appearance and constitute around 90% of the known outcrops of the Uivak gneiss group. The Uivak II gneisses are coarse grained augen gneisses which locally preserve porphyritic or megacrystic textures of "igneous" appearance. They are chemically distinct from the Uivak I gneisses, being generally more potassic and displaying a significant iron enrichment trend (Collerson and Bridgwater, 1979). In areas of low intensity deformation, they are seen to intrude strongly layered Uivak I gneisses. Both sub-groups are of different ages and are separated in time by extensive deformation, metamorphism and migmatisation.

The second group of quartzofeldspathic gneisses, the Kiyuktok gneisses, are heterogeneous rocks which are believed to have developed by the in situ melting and mobilisation of the Uivak gneisses. True "Uivak" and "Kiyuktok" gneisses can thus be regarded as end-members of a continuous series of rocks which are increasingly reworked towards the "Kiyuktok" end of the series. In the field, most of the quartzofeldspathic gneisses are rocks of mixed character in which both a relict "Uivak" component and a reworked "Kiyuktok" component can be distinguished. The term "reworked" is used here according to the definition presented in Chapter 1.

Most of the quartzofeldspathic gneisses east of the Middle Cove fault zone display only minimal reworking and are assigned to the Uivak gneiss group. Good examples of Kiyuktok gneisses are, however, present on a local scale at Torr Bay. To the west of the fault zone, the gneisses are extensively reworked.

These rocks usually contain over 70% Kiyuktok component and are termed Kiyuktok gneisses. Problems of terminology arise in some areas (notably Kiyuktok Cove and Fire Cove) where gradational transitions between layered Uivak gneisses and structureless Kiyuktok gneisses are observed. In such cases, the resultant rocks are termed Kiyuktok gneisses where the reworked component is volumetrically dominant over the relict Uivak component. This definition is admittedly rather imprecise, but it is the simplest method of delineating the two groups of gneisses upon the scale of the map.

The appearance of the Kiyuktok gneisses varies with the extent of reworking. They range from recognizable derivatives of the Uivak suite to structureless nebulites (c.f. Mehnert, 1969) and ultimately to intrusive pegmatitic rocks in areas of high mobility. The contrasts between the Uivak and Kiyuktok gneisses are listed in Table 2.

A third group of quartzofeldspathic gneisses is present on a very small scale within the study area. These are known as the Ikarut gneisses (Collerson, Kerr and Compston, 1980) and characteristically occur as discordant sheets of foliated dioritic, tonalitic and granodioritic material. They lack the complex polyphase history of the Uivak and Kiyuktok gneisses and appear to have been emplaced at a relatively late stage in the evolution of the gneiss complex. Their relationship to the Kiyuktok gneisses is presently equivocal; field evidence (3.4) and radiometric evidence (Collerson, Kerr and

Compston, 1980) suggests that they are of broadly equivalent ages.

Although volumetrically insignificant in the Saglek area, the Ikarut gneisses are widespread in the Hebron and Nachvak areas, where they form thick units concordant with the regional layering of the complex. Their importance as a constituent of the gneiss complex elsewhere in eastern Labrador remains to be evaluated.

3.2. THE UIVAK GNEISSES

3.2.1. Introduction

Within the study area, the Uivak gneisses have been variably affected by the events which caused the formation of the heterogeneous group of rocks known as the Kiyuktok gneisses. Thus, over much of the area, the earlier gneisses are recognizable only as isolated remnants within remobilized material, and sometimes merely as a "ghost" layering in younger nebulites.

Uivak gneisses showing only minimal effects of reworking are mostly preserved east of the Middle Cove fault zone but are unfortunately rather poorly exposed throughout. The best outcrops occur along a well-exposed and clean coastal strip on the west side of Torr Bay. West of the Middle Cove fault zone, well-preserved Uivak gneisses are restricted to two areas. The larger of the two is contained within the core of an early fold in the Fire Cove supracrustal belt, but is not exposed on the coast. A smaller area in the core of a megascopic antiform at Kiyuktok Cove provides excellent exposures of Uivak gneisses, and also yields information concerning the processes by which the Kiyuktok gneisses developed.

The majority of these Uivak gneisses are strongly layered rocks and can probably be assigned to the Uivak I sub-group of Bridgwater and Collerson (1976). Uivak II gneisses outcrop within the core at the Fire Cove belt and also in small quantities at Torr Bay.

However, recognition of the Uivak II gneisses by field criteria alone becomes very difficult in areas of high strain, where even the coarsest augen textures are totally obliterated. In such cases, discrimination between the two groups may only be effected by geochemical methods.

3.2.2. Uivak I Gneisses

Most of the Uivak I gneisses are compositionally layered rocks of "migmatitic" appearance. However, a small number of exposures within areas of relatively weak deformation consist of homogeneous trondhjemitic, tonalitic and granodioritic rocks of meta-igneous appearance (Plate 1). These rocks will be considered before the more abundant layered rocks because it is likely that they represent the closest approach to the protoliths of the Uivak I sub-group. Within the study area, these rocks are most abundant at Torr Bay and Kiyuktok Cove. Outside of the study area, they are best known at Saglek Bight

Plate 1 . Homogeneous tonalitic Uivak I gneiss, Big Island . Note earlier mafic phase at right and layered gneisses at upper left .

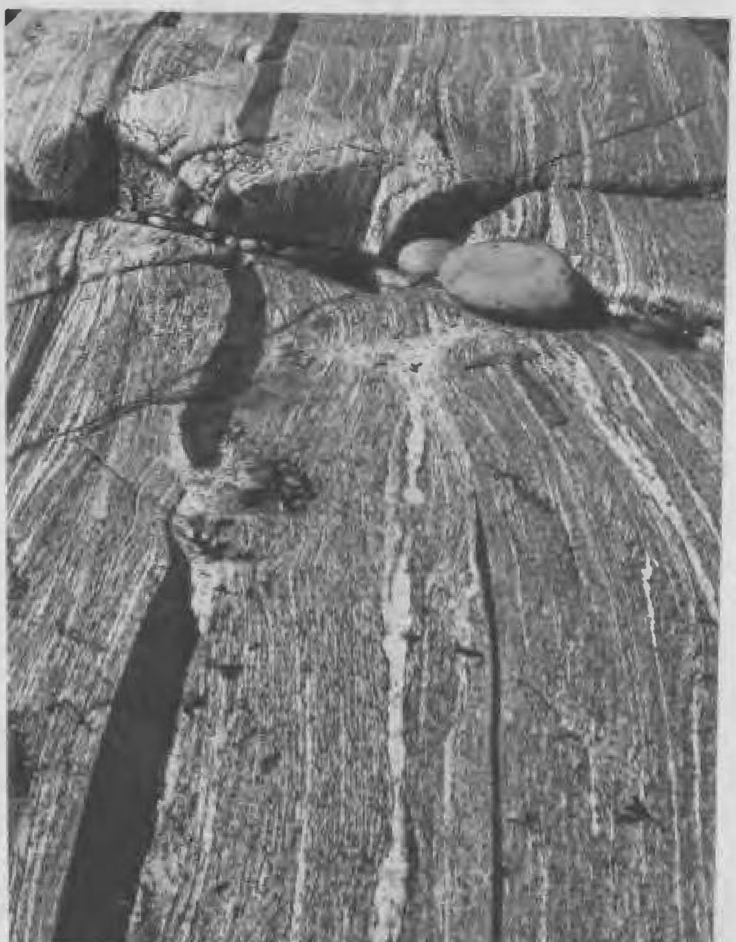


Plate 2 . Layered Uivak I migmatites containing disrupted Saglek dykes . Coast opposite Nulliak Island . Photo courtesy of K.D.Collerson .

on the south coast of Big Island (Fig. 5). Important chronological relations are also preserved at this locality and provide important information regarding the early history of the complex.

The homogenous grey gneisses typically consist of quartz (10-30%), plagioclase (45-60%), biotite and/or hornblende (5-15%) and potash feldspar (0-15%). In terms of equivalent igneous rocks, they are best classified as diorites, trondhjemites and tonalites. They are generally medium-grained rocks with an average grain size of about 1 mm. A foliation is defined by the alignment of biotite flakes and is sometimes also reflected in the elongation of quartz and feldspar grains. This foliation invariably parallels the compositional layering in surrounding rocks. It is sometimes possible to recognize an earlier mafic phase which is cut by the dominant tonalitic or trondhjemitic material.

Throughout most of the area, the Uivak I gneisses are monotonous migmatitic rocks (Plate 2). These are the "banded grey gneisses" which are typical of vast expanses of early continental crust elsewhere in the world. The compositional layering in these rocks is defined by the alternation of grey, biotite-rich layers with a coarse-grained quartz-plagioclase-microcline pegmatite. The pegmatitic ("leucosome") fraction usually makes up between 10 and 40% of the rock by volume. The grey, biotite-bearing "melanosome" is similar in most respects to the homogeneous gneisses described above, but generally shows a stronger foliation. The scale of the compositional layering varies from less than 1 mm to greater than 1 m, but is usually in the range 1-10 cm. The foliation within the melanosome is invariably parallel to this layering. Most of the pegmatitic "leucosome" layers are discontinuous upon an outcrop scale and take the form of lenses or schlieren between 1 and 5 m in length. Some of the thicker pegmatites are more continuous and can be traced along strike for distances of up to 25 m.

Virtually every outcrop of the Uivak I gneisses contains at least two sets of pegmatite layers which are of different ages. A fine scale layering is defined by discontinuous stringers which frequently take the form of rootless intrafolial folds (Plate 3). Thicker pegmatite sheets in the same outcrops can be traced for greater distances and locally transgress the foliation which parallels the earlier discontinuous layering. These thicker pegmatites are sometimes seen to cut Saglek dykes in the gneisses and are thus relatively late features in some areas, perhaps related to the development of the Kiyuktok gneisses. In other instances, however, the thicker, concordant pegmatites may pre-date the intrusion of the Saglek dykes.

3.2.3. The Uivak II Gneisses

Members of the Uivak II sub-group are a minor but highly distinctive component of the quartzofeldspathic gneiss

Plate 3 . Rootless intrafolial fold in layered Uivak I migmatites ,
St. John's Harbour .
Photo courtesy of K.D.Collerson .

Plate 4 . Slightly deformed Uivak II gneisses preserving original porphyritic textures and enclosing a xenolith of Uivak I layered gneiss . Coast opposite Nulliak Island .
Photo courtesy of K.D.Collerson .

complex. Within the study area, they are most abundant, and best preserved, in an elongate belt which occupies the central part of the Fire Cove supracrustal belt. They also occur in smaller quantities at Torr Bay where they are intercalated with layered gneisses of the Uivak I sub-group.

The differences between the Uivak II gneisses and the more abundant Uivak I gneisses are both lithological and geochemical. In terms of field characteristics, Uivak II gneisses are distinguished by their coarser grain size, higher modal content of mafic minerals and by characteristic megacrysts or augen of potash feldspar. In areas of very high strain, however, there is some difficulty in discrimination by these means alone.

In areas of relatively weak deformation, such as the central part of the Fire Cove belt, the Uivak II gneisses are clearly recognizable as metamorphic derivatives of porphyritic granodiorites, adamellites and granites (Plate 4). Although original relationships with the Uivak I gneisses are not seen in this area, Uivak II protoliths are clearly seen to intrude the latter on Big Island and Mentzel Island (Collerson and Bridgwater, 1979). At these localities, the Uivak I gneisses already possessed a strong compositional layering at the time of emplacement.

In the Fire Cove area, the Uivak II gneisses are of adamellitic composition and consist of quartz (20-30%), potash feldspar (10-25%), plagioclase (30-40%) and biotite/hornblende

(10-15% in total). In other areas, such as Torr Bay and Maidmonts Island, they contain a higher percentage of mafic minerals, but retain broadly similar ratios between quartz, plagioclase and potash feldspar.

Grain size is variable; in slightly deformed areas, individual megacrysts range up to 5 x 2 cm and the groundmass (quartz + plagioclase + mafics) averages at 4-5 mm. With increasing deformation, individual megacrysts become progressively more difficult to recognize, but the overall grain size remains three or four times greater than in the Uivak I gneisses.

The strong L or L-S fabrics which develop in the Uivak II gneisses transform the porphyritic igneous textures into porphyroclastic augen textures (Plate 5). Originally angular megacrysts become rounded and are sometimes extensively stretched, reaching aspect ratios of 30:3:1 in extreme examples. In zones of very high strain, the feldspar megacrysts become so extensively flattened that a crudely layered gneiss is formed. Rocks of this type appear to be widespread at Torr Bay where augen textures are preserved in the closures of isoclinal folds but converted into a crude layering along the limbs (Plate 6).

3.2.4. The Saglek Dykes

One of the most important features which allows recognition of the Uivak gneisses in the field are the amphibolite inclusions which Bridgwater et al. (1975) termed the Saglek dykes. These form an integral part of the quartzo-

Plate 5 . Strongly deformed Uivak II gneiss displaying porphyro--clastic "augen" texture and crude compositional layering, Coast opposite Nulliak Island .
Photo courtesy of K.D.Collerson .

Plate 6 . The core of an isoclinal fold in Uivak II augen gneisses, Torr Bay . The augen are well preserved in the closure , but highly attenuated along the limbs , where a compositional layering is developed .

feldspathic portion of the gneiss complex and are hence described in this chapter.

In view of their importance in field work, it is imperative that their characteristics are defined within narrow limits. The term "Saglek dyke" is thus restricted to those amphibolite bodies which contain recognizable megacrysts or aggregates of plagioclase. These rocks generally consist of hornblende (45-70%) and plagioclase. Grain size within the groundmass varies from 0.5 mm to 3 mm; a foliation or lineation is defined by hornblende. Individual megacrysts of plagioclase range up to 4 x 2 cm in size, but are usually in the range 1 x 0.5 cm to 2 x 1 cm. Euhedral crystal shapes are sometimes observed, but megacrysts are more often of ovoid shape. The amount of megacrysts within individual dykes is variable; where they are particularly abundant, they are often seen to be concentrated along one margin of the dyke.

Within strongly layered gneisses, Saglek dykes typically occur as elongate, lensoid bodies between 2 and 10 m in length and between 10 cm and 1 m in width. These lenses are parallel to the gneissic layering and foliation and show sharp contacts with surrounding gneisses (Plate 7). They are intimately folded with the gneisses and form trails of boudins parallel to the regional gneissosity.

Discordant Saglek dykes have not yet been observed in the study area, but are known from enclaves of low deformation at White Point, Big Island and Mentzel Island. At

Plate 7a . Concordant Saglek dykes in layered Uivak I migmatites , West shore of Torrbay . Note complex folding at right .

Plate 7b . Discordant Saglek dyke truncating complex interference structures in layered Uivak I gneisses , White Point . Photo courtesy of K.D.Collerson .

White Point, the dykes are seen to truncate complex interference patterns which were developed in the layered gneisses prior to their intrusion. The generally concordant nature of the Saglek dykes in most parts of the Saglek-Hebron area is interpreted as a result of transposition by repeated isoclinal folding. It is possible, however, that many members of the swarm were intruded as concordant sheets in response to the anisotropy provided by the pre-existing gneissic layering. Either scheme would explain the present rarity of discordant contacts, but the first hypothesis is preferred by the author.

Saglek dykes have only rarely been observed to cut the Uivak II gneisses, but are known to do so on Mentzel Island. This rarity is rather surprising in view of the common occurrence of dykes within Uivak I gneisses. Collerson (pers. comm., 1979) suggests that it may reflect the more isotropic nature of the Uivak II gneisses; they may simply have been more difficult to intrude.

3.3. THE KIYUKTOK GNEISSES

3.3.1. Introduction

The Kiyuktok gneisses are the most abundant of the three groups of quartzofeldspathic rocks and underlie most of the area west of the Middle Cove fault zone. They also occur on a local scale at Torr Bay. They are rocks of mixed character comprising a relict (Uivak) component and a reworked

TABLE 2: Characteristics of Relict and New Components in the Kiyuktok Gneisses.

Relict (Uivak) Component	New Component
Fine scale layering defined by melanocratic and leucocratic layers	No compositional layering
Strong foliation parallel to compositional layering and defined by alignment of biotite/ hornblende and elongation of quartz and feldspar	Generally massive and non-foliated except where strongly affected by later events
Mafic minerals evenly distributed throughout melanocratic layers	Mafic minerals localised into clots, which are distributed irregularly through the rock
Well preserved Saglek dykes with sharp, sometimes discordant contacts with their host rocks	Saglek dykes are cut by and partially resorbed by the new component
Sharp (tectonic??) contacts with post-Uivak supracrustals	Locally intrusive contacts supracrustal rocks
Normally less than 20% modal microcline	Up to 60-70% modal microcline

(Kiyuktok) component. Visual estimates made in the field suggest that the latter typically constitutes over 70% of the rocks by volume.

The Kiyuktok gneisses are best studied in clean, ice-scoured coastal outcrops and are particularly well exposed at Kiyuktok Cove, Fire Cove and Middle Cove. The most important outcrops, however, are at Kiyuktok Cove itself, where the progressive transformation of the Uivak gneisses is beautifully displayed. Observations made largely at this locality form the basis for the discussion of the development of the Kiyuktok gneisses in section 3.3.3. Outside of the enclaves at Kiyuktok Cove and Fire Cove, the rocks along the coast have been extensively reworked and are largely rather featureless nebulites. There are also numerous inland exposures of the Kiyuktok gneisses in the mountains northeast of Heart Lake and between Fire Cove and Banana Lake. However, the thick lichen crust which exists at lower altitudes obscures the contrasts between the Uivak and Kiyuktok components and hampers evaluation of their relative importance. As these outcrops are within a zone which was strongly deformed after the formation of the Kiyuktok gneisses, interpretation of the relationships between the two components is commonly equivocal. Nevertheless, observations made upon the cleanest and least deformed outcrops suggests that the Kiyuktok gneisses in this area are extensively reworked Uivak gneisses similar to those at Middle Cove and between Fire Cove and Kiyuktok Cove.

3.3.2. General Features

In the field, the Kiyuktok gneisses can be described in terms of two components, i.e. a relict "Uivak" component and a more abundant "Kiyuktok" component, which is interpreted as reworked Uivak material. Lithological features of the two components are summarized in Table 2.

The Uivak component is identical in most respects to the unreworked Uivak gneisses (see section 3.2) and will not be described in detail here. In most cases, it displays a strong compositional layering and is therefore most probably of Uivak I origin. Occasionally, as at Fire Cove, the relict component is a coarse-grained granodioritic or granitic rock resembling a strongly deformed Uivak II gneiss.

In contrast, the Kiyuktok component is a massive yellow or brown weathering rock which lacks any form of compositional layering. It is generally coarse grained, with average grain sizes between 2 and 5 mm. Mineralogically it consists essentially of quartz (24-25%) and feldspar (50-75%), with potash feldspar forming between 20 and 50% of the total feldspar content. The principal mafic phase is biotite, which is present in variable amounts (1-15%).

Instead of being concentrated in discrete layers, as in typical Uivak gneisses, the mafic minerals occur in glomeroporphyroblastic patches, for which the term "clots" is used. Individual "clots" are roughly spherical in shape, with diameters ranging from less than 2 mm to over 2 cm and

Plate 8 . Nebulitic Kiyuktok gneiss locally preserving a compositional layering inherited from the Uivak gneisses . 1.5 km N.E. of Kiyuktok Cove .

Plate 9 . Kiyuktok gneiss with "ghost" layering and disrupted Saglek dyke remnant , Middle Cove .

averaging at about 6 mm. They are composed mostly of biotite, but the cores of some of the larger examples contain garnet or orthopyroxene, which is rimmed by fine-grained biotite.

In most of the coastal outcrops, the Kiyuktok component within the gneisses is massive and non-foliated. However, in some inland areas which were affected by late Archean deformation (and particularly adjacent to the Heart Lake zone) it has acquired a moderate to strong foliation defined by the elongation and alignment of the mafic clots.

Outside of the transitional areas at Kiyuktok Cove and Fire Cove, the Kiyuktok component within the gneisses is generally greater than 70% by volume. These extensively reworked rocks are extremely heterogeneous upon an outcrop scale (Plates 8 and 9). In most cases, however, it is still possible to recognize a relict Uivak layering which is transgressed and obliterated by the reworked component. In some areas, and particularly at Middle Cove, the proportion of reworked material becomes so high that relict Uivak features are lost completely. The resultant rocks appear almost totally structureless (Plate 10) and are best termed "nebulites" (c.f. Mehnert, 1969). Some of these rocks locally intrude Upernavik supracrustal lithologies and must therefore have been mobile at some point in their history. However, others contain amphibolite inclusions which contain feldspar megacrysts and would therefore appear to be remnants of Saglek dykes, suggesting that *in situ* transformation of the Uivak gneisses played at least some part in the generation of the nebulites.

The nebulitic rocks exposed at Middle Cove are believed to represent the end product of the reworking process and retain very little evidence of their Uivak parentage. In extensively reworked rocks such as these, it is very difficult to infer anything about the processes which were responsible for the transformation of the Uivak gneisses. In order to study the progressive development of the Kiyuktok gneisses, we must turn to the slightly reworked areas at Kiyuktok Cove and Fire Cove.

3.3.3. The Development of the Kiyuktok Gneisses

The progressive transformation and reconstitution of the Uivak gneisses is best studied at Kiyuktok Cove and Fire Cove. This is because (a) the reworking process did not proceed to completion in these areas, and (b) both areas were relatively unaffected by the late Archean deformation prevalent elsewhere in the area. Consequently, they preserve original, unequivocal relationships between the Uivak and Kiyuktok gneisses which have been obliterated by further reworking and/or later deformation at most other localities.

At these localities, it is possible to distinguish between Kiyuktok gneisses which appear to have formed by *in situ* reconstitution of the Uivak parent and others whose reworked component was derived elsewhere and subsequently emplaced into the Uivak gneisses. The Kiyuktok component in both types of Kiyuktok gneiss is identical and the two can be distinguished only on the basis of their relationships with

Plate 10 . Nebulitic Kiyuktok gneiss containing glomerporphyroblastic aggregates ("clots") of biotite and preserving a "ghost" layering at left . Kiyuktok Cove .

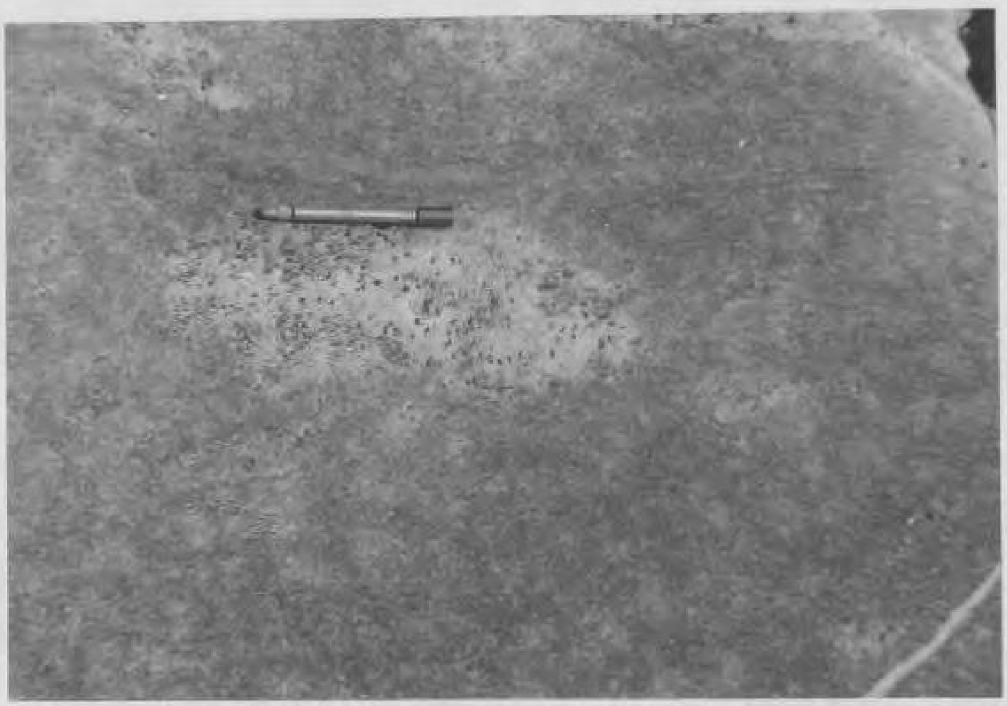


Plate 11 . Irregular patch of "new" (Kiyuktok) component enclosed in a homogeneous Uivak I gneiss . Kiyuktok Cove .

the relict Uivak component. There is strong evidence to suggest that the two processes are intimately related; this will be discussed below.

(I) IN SITU DEVELOPMENT:

The *in situ* development of the Kiyuktok gneisses is most easily recognized when it occurs within homogeneous Uivak gneisses in the form of irregular patches (Plate 11). These are roughly spherical or oval and range between 10 cm and 2 m in diameter. They are completely surrounded by the host Uivak gneiss and their contacts with it, although apparently sharp from a distance, are invariably diffuse and gradational. Within compositionally layered Uivak gneisses, the *in situ* Kiyuktok component commonly occurs as irregular lenses and stringers oriented parallel to the Uivak layering (Plate 12). These lenses and layers of reworked material are discontinuous upon an outcrop scale and frequently contain a "ghost" layering defined by the melanocratic portion of the Uivak gneisses, which appears to have resisted transformation. Contacts with the surrounding Uivak gneisses are diffuse and gradational.

In many examples, several individual lenses coalesce into a single large, irregular patch of Kiyuktok component.

(II) INTRUSIVE DEVELOPMENT:

Kiyuktok gneisses whose reworked component appears to be largely of intrusive origin are widespread at Kiyuktok Cove and Fire Cove. The intrusive Kiyuktok component is most

Plate 12 . Irregular stringers and lenses of "new" (Kiyuktok) component in a layered Uivak I gneiss , Kiyuktok Cove . The fine-grained discordant material in the upper half of the photo is a later tonalite sheet assigned to the Ikarut gneisses .

easily recognized when it occurs in the form of discordant sheets and vein networks in otherwise unaffected Uivak gneisses (Plate 13). In some areas the proportion of intrusive material becomes so high that Uivak gneisses are preserved only as disrupted and rotated blocks (Plate 14).

Intrusive Kiyuktok components more commonly occur as concordant or sub-concordant sheets which locally transgress the earlier layering and foliation. The best examples of Kiyuktok gneisses formed in this manner are at Fire Cove, where the rocks have a "lit-par-lit" appearance (Plate 15). These intrusive sheets vary widely in size, ranging from veinlets less than 1 cm across to massive bodies whose thickness is measured in tens of metres. Some of these larger sheets occur within otherwise unreworked Uivak gneisses at Torr Bay.

Contacts between the Kiyuktok component and the Uivak country rocks are variable in appearance. In some of the smallest examples they are sharp but, in most cases, they are characterized by a border zone in the country rocks where *in situ* transformation takes place (Plate 16). Some of the larger sheets of Kiyuktok pegmatite have completely gradational contacts with surrounding Uivak gneisses which may indicate that they formed in situ. However, when traced along strike, some of these bodies display sharp, intrusive contacts with an extensive border zone of in situ reconstitution. This suggests that the diffuse nature of their contacts in other

Plate 13 . Homogeneous Uivak I gneiss net-veined by coarse-grained intrusive pegmatites forming part of the Kiyuktok Suite. Kiyuktok Cove .

Plate 14 . A more advanced stage of the above where the Uivak gneisses are preserved only as xenoliths . Kiyuktok Cove .

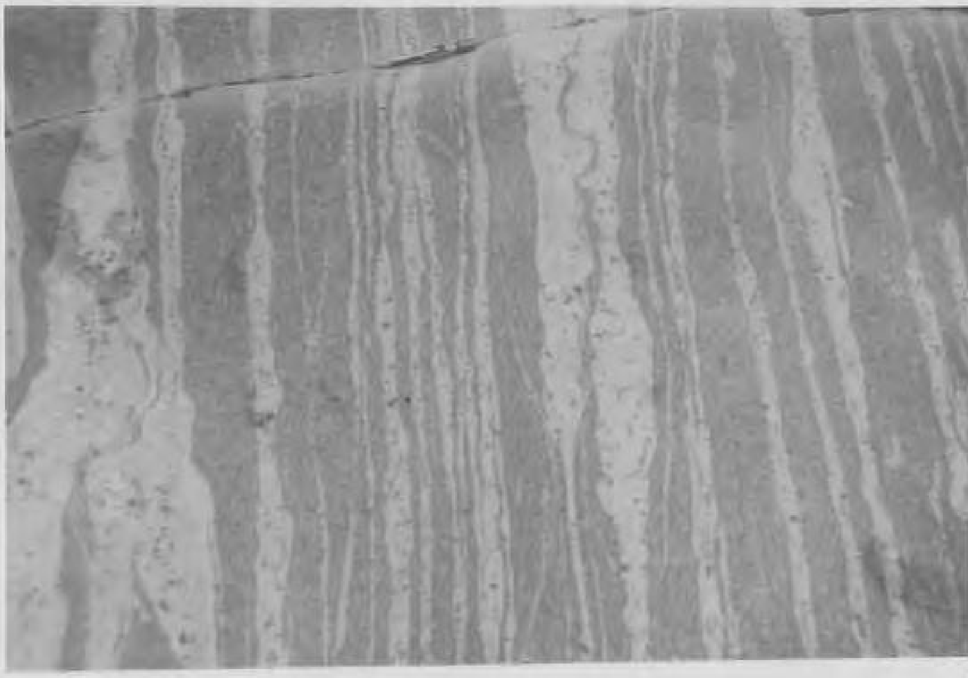


Plate 15 . Kiyuktok pegmatites emplaced in a lit-par-lit fashion into a strongly deformed Uivak II gneiss , Fire Cove .

Plate 16 . A border zone of in situ reconstitution developed around the margins of an intrusive pegmatite . Kiyuktok Cove .

areas results from the obliteration of originally intrusive relationships by large-scale border zone development.

Examples are known of Kiyuktok gneisses which developed wholly by in situ transformation or wholly by the emplacement of externally derived pegmatitic material. More commonly, however, the two processes are seen in close association within the same outcrops and the in situ transformation often appears to have been triggered by the intrusion of the pegmatites, to which it bears a clear spatial relationship. The intrusive material is macroscopically indistinguishable from the Kiyuktok component which has formed in situ. This strongly suggests that the intrusive pegmatites were initially formed by a similar process which eventually resulted in the formation of a mobilizate.

It seems, therefore, that the in situ and intrusive development of the Kiyuktok gneisses are intimately related phenomena which operated together. It seems reasonable to assume that the structureless Kiyuktok nebulites which underlie much of the study area were also produced by a combination of these two processes, even though they retain little or no evidence of their origin.

3.4. THE IKARUT GNEISSES

The Ikarut gneisses are a group of rocks of limited extent which have so far been identified at Nachvak, Hebron and Saglek. They were recognized initially in the Saglek area where they are a very minor component of the gneiss complex which were known simply as "grey dykes". The recognition of large bodies of similar rocks along a portion of Hebron Fjord known as "Ikarut" led to the introduction of the present nomenclature by Collerson, Kerr and Compston (1980). Rocks of similar aspect in the Nachvak Fjord area are known as the Kammarsuit gneisses, but field and isotopic evidence (Collerson, Kerr and Compston, 1980) suggests that they are also members of the Ikarut suite.

In the type area, the Ikarut gneisses are large bodies which are sub-concordant upon a regional scale with the layering of the pre-Ikarut gneiss complex. Contacts with the Uivak gneisses, and with most of the Kiyuktok gneisses, are discordant and almost certainly represent originally intrusive relationships. They are fine to coarse-grained rocks containing 5-25% quartz and 5-30% mafics (largely biotite and/or hornblende). The remainder is feldspar which is usually largely plagioclase with small (0-20%) quantities of K-feldspar. A few quartz-rich varieties contain larger quantities (up to 50%) of K-feldspar.

The Ikarut gneisses are thus mineralogical equivalents of diorites, quartz diorites, tonalites, granodiorites, adamellites and granites, with the more mafic compositions predominating. Where it is possible to analyze relationships between the different varieties, rocks of more mafic composition are usually seen to be the earliest members of the sequence.

Texturally, the Ikarut suite ranges from homogeneous fine-grained rocks to coarse-grained rocks with spectacular porphyritic or (in areas of more intense deformation) porphyroclastic textures. Phenocrysts or augen consist either of plagioclase or K-feldspar, or both. The textures displayed by the Ikarut gneisses, and their relationships with one another and the Uivak gneisses, are highly suggestive of those displayed by plutonic igneous rocks and there seems little doubt that they were once rocks of this type.

However, they have undoubtedly been deformed since strong fabrics are developed in some examples. The fabrics are defined by the alignment of mafic minerals, and, in originally porphyritic rocks, by strong porphyroclastic textures. The most strongly deformed rocks are usually found in marginal parts of the units, whereas the interiors are comparatively undeformed. There is no evidence of composite fabrics amongst members of the Ikarut suite, and migmatitic layering is completely absent.

Within the study area, and in other parts of the Saglek district, the Ikarut gneisses very rarely form units of mappable dimensions and normally occur as thin (<5 m) sheets and dykes which are discordant to the Uivak gneisses (Plate 17). They are widely distributed throughout the area and display a range of compositions comparable to that of the more extensive examples at Hebron, but are generally fine to medium grained and non-porphyritic. The degree of deformation

Plate 17 . A multi-phase tonalitic intrusive body at Kiyuktok Cove . Note that the earlier (darker) phase is cut by a Kiyuktok pegmatite , which is itself truncated by a later phase . This demonstrates the synchronous nature of the Kiyuktok gneisses and the late Archean intrusive rocks .

Plate 18 . A thin sheet of foliated tonalite which cuts both Uivak and Kiyuktok gneisses . Kiyuktok Cove .

in these minor intrusions is also variable. In areas where Late Archean upright folds (see Chapter 9) are prominent, strong fabrics are defined by biotite alignment. Outside of these zones, however, many Ikarut gneisses appear to be almost undeformed in outcrop.

The Ikarut sheets and dykes are invariably intrusive into the Uivak gneisses but their relationships with the Kiyuktok gneisses are somewhat equivocal. In most outcrops, they clearly cross-cut both Uivak and Kiyuktok components (Plate 18). At Kiyuktok Cove, however, intrusive pegmatites forming part of the Kiyuktok gneisses are seen to cut homogenous grey tonalitic and granodioritic rocks which themselves show intrusive relationships with the Uivak gneisses. It seems reasonable to assign these rocks to the Ikarut suite, which suggests that the development of the Kiyuktok gneisses and the emplacement of the Ikarut gneisses was partly contemporaneous in this area at least.

The recognition of pre-Kiyuktok Ikarut gneisses at Kiyuktok Cove is only possible because the effects of reworking were limited in this area. In the heavily reworked rocks which exist elsewhere, recognition of early Ikarut gneiss sheets would be completely impossible as they would probably be reworked in the same fashion as the Uivak gneisses.

The Ikarut gneisses are similar in many respects to the Nuk gneisses of West Greenland which are described by McGregor (1973), with which they are tentatively correlated (Collerson, Kerr and Compston, 1980).

Plate 19 . Agmatite consisting of numerous blocks of different rock types enclosed in a weakly foliated granitoid matrix , Torr Bay . The agmatites contain blocks of Kiyuktok gneiss , but are cut by pegmatite sheets assigned to the Igukshuak granite suite . This suggests that they are similar in age to the Ikarut gneisses , to which they may be genetically related .

The extensive zone of agmatites which outcrops between Middle Cove and Torr Bay (see map) is probably broadly equivalent in age to the Ikarut gneisses. Its development clearly post-dates the reworking of the gneiss complex since blocks of Kiyuktok gneiss are enclosed by the agmatite leucosome. This leucosome is itself cut by post-tectonic pegmatites which are believed to form part of the Igukshuak granite suite, which is about 2,520 Ma old (Baadsgaard et al., 1979). The agmatites are macroscopically heterogeneous rocks which consist of numerous disoriented blocks of both supracrustal and basement lithologies enclosed in a weakly foliated "granitoid" matrix which is lithologically similar to some of the Ikarut gneisses (Plate 19). Until further geochemical and isotopic work is conducted, the agmatites are regarded as part of the Ikarut suite.

CHAPTER 4

QUARTZOFELDSPATHIC GNEISSES -- PETROLOGY

4.1. INTRODUCTION

This chapter describes the petrology of the quartzofeldspathic gneisses in detail and is based upon a study of over 100 thin sections. It is intended to be largely descriptive, and serves as a data base for discussions contained in Chapter 5.

It is logical to describe the Uivak gneisses first, since they are the oldest group of rocks and represent the parent rocks to the Kiyuktok gneisses.

The Kiyuktok gneisses are treated in terms of "components" and are split into three categories: i.e. (1) components of external (intrusive) origin, (2) components which formed in situ within the Uivak gneisses, and (3) nebulitic Kiyuktok gneisses of uncertain origin. The Uivak component in heavily reworked rocks is also described in this section.

The Ikarut gneisses are briefly described in the final section.

4.2. THE UIVAK GNEISSES

4.2.1. Uivak I Grey Gneisses

The well preserved, macroscopically homogeneous grey gneisses contained within enclaves which escaped the full effects of later deformation and metamorphism are a logical starting point for this section as they probably represent the closest approach to the original characteristics of the Uivak suite. Major mineral assemblages in these rocks are as follows:

(1) Quartz-plagioclase-biotite
(2) Quartz-plagioclase-biotite-hornblende
(3) Quartz-plagioclase-microcline-biotite
(4) Quartz-plagioclase-microcline-biotite-hornblende.

Although assemblages (1) and (2) are sometimes observed, the majority of the gneisses contain small (normally less than 10%) amounts of microcline. Apatite, epidote, allanite and zircon are common as accessory phases and sphene and monazite occur in a few specimens.

It is informative to consider the above assemblages in terms of equivalent mineral assemblages in acid and intermediate plutonic rocks. This allows a tentative classification on the basis of plagioclase: alkali feldspar ratios and the overall abundance of quartz, which is the normal procedure for such rocks. Variations in these parameters suggests that the Uivak I grey gneisses have igneous equivalents in tonalites, trondhjemites and granodiorites. This is not by itself proof that the gneisses were derived from such protoliths but terms such as "tonalitic gneiss" are valuable in a descriptive sense and will be retained. Field evidence (5.2.) and geochemical evidence (Collerson and Bridgwater, 1979) does, however, strongly suggest that the Uivak I gneisses are derivatives of intrusive rocks.

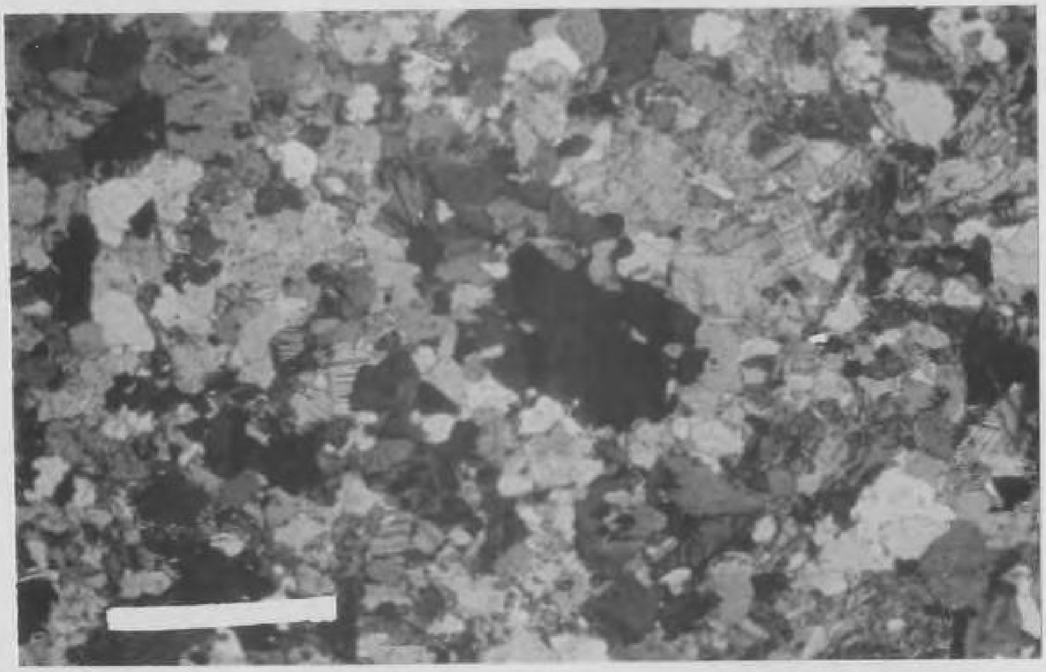


Plate 20 . Macroscopically homogeneous Uivak I tonalitic gneiss in thin section . Note coarse-grained and fine-grained domains. Details of these domains are shown in Plates 21-23 . Crossed nicols . Scale bar 2mm .

Although macroscopically homogeneous in the field (see Plate 1), most of the grey gneisses display considerable heterogeneity in thin section, which is expressed by contrasting coarse-grained and fine-grained domains upon a scale of a few millimeters (Plate 20). This heterogeneity is caused solely by variation in the grain size of quartz and K-feldspar; plagioclase and the mafic minerals are of constant size throughout. Average grain sizes range from approximately 1 mm in coarse domains to between 0.1 and 0.3 mm in the finer domains. The frequency distribution of grain size is effectively bimodal; very few grains of intermediate dimensions are seen.

Quartz is the most prominent constituent and is present in two forms. It is most noticeable in the coarse domains where it forms irregular anhedral grains up to 2 mm in diameter which show well-developed deformation bands and sub-grain structure. These large grains almost always occur in clusters in which all the individuals are optically continuous and in which the orientation of deformation bands is constant (Plate 21). They are sometimes slightly elongated, with the elongation paralleling the foliation defined by biotite alignment elsewhere. Deformation structures within quartz grains are usually aligned with this foliation. These large clusters of grains are regarded as two-dimensional expressions of complex three-dimensional amoeboid shapes. Grain boundaries between these grains and other phases tend to be embayed, scalloped or sutured (terminology after Spry, 1969).

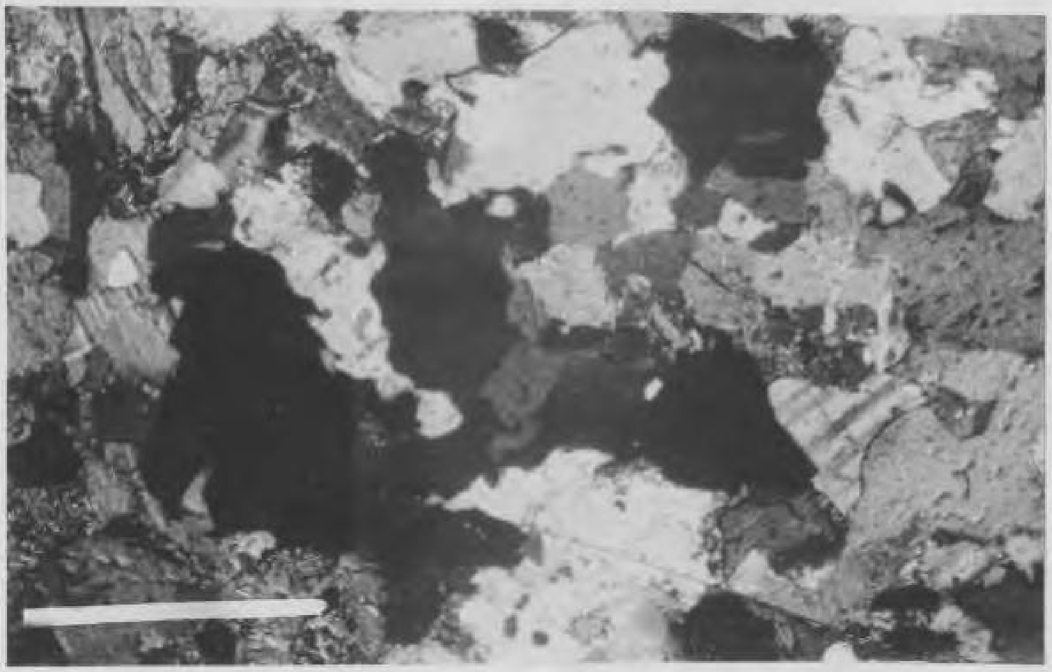


Plate 21 . Detail of coarse-grained domain : A large amoeboid quartz grain at extinction . Crossed nicols . Scale bar 1 mm .

Plate 22 . Detail of fine-grained domain : Fine grained , strain-free polygonal aggregate of quartz and microcline . Crossed nicols . Scale bar 0.2 mm .

Quartz also occurs as polygonal aggregates of small (less than 0.2 mm average diameter) optically strain-free grains, where it is accompanied by microcline of a similar size range (Plate 22). Boundaries between phases in these fine-grained domains approach stable configurations with 120^{o} interfacial angles. Small quartz and microcline grains similar to those in the fine-grained domains are also found as inclusions within the larger amoeboid grains.

The dominant feldspar in the grey gneisses is plagioclase whose composition is usually in the range $Ab_{75}An_{25}$ and $Ab_{80}An_{20}$ (estimated by optical methods and electron microprobe analysis). It occurs as large, subhedral grains ranging in size from 0.5 x 0.5 mm to over 2 x 2 mm. These grains do not show well-defined albite twin lamellae and usually display strongly undulose extinction. Where twin lamellae are visible, they are faded, indistinct and deformed (Plate 23).

Where K-feldspar is present, it is invariably microcline and occurs as small polygonal grains showing well-defined cross-hatched twinning. In some cases only one twin direction is visible and the microcline is easily confused with plagioclase. However, staining techniques and microprobe analysis shows quite clearly that virtually all of the fine-grained feldspar is potassic. It is not visibly perthitic. Myrmekite is observed at some plagioclase-microcline interfaces.

Plate 23 . Detail of coarse-grained domain : A large , strained oligoclase grain with poorly defined twinning . Plagioclase of this type is typical of the Uivak gneisses . Crossed nicols . Scale bar 1 mm .

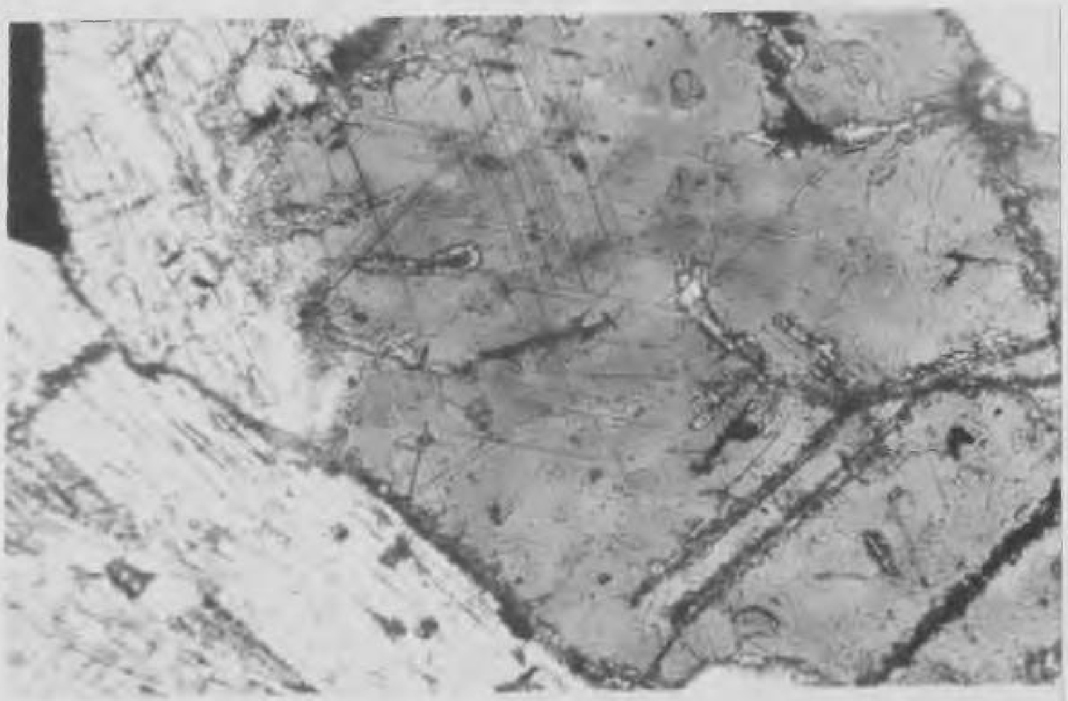


Plate 24 . "Sagenitic" biotite in a Uivak I granodioritic gneiss . Plane polarised light . Scale bar 1 mm .

The principal mafic phase in the gneisses is biotite which is strongly pleochroic from pale yellow (X) to very dark brown (Y = Z). It is present either as sub-idioblastic flakes up to 2 mm in length, or as lepidoblastic aggregates up to 5 x 5 mm in size. It is locally replaced by muscovite which overgrows the biotite in crystallographic continuity. The biotite is a notably iron-rich variety containing up to 25 wt % FeO.

A very distinctive feature of biotite in the Uivak gneisses is the presence within it of numerous crystallographically oriented needles of rutile (Plate 24). This type of texture is commonly described as "sagenitic" (Hatch, Wells and Wells, 1972, p. 104).

Pleochroic green amphibole containing minute inclusions of ilmenite and spinel is commonly observed in association with biotite. It is usually found in the central portions of biotite aggregates, where it is overgrown and replaced by the biotite. The development of the rutile needles in the biotite may have taken place at the same time as the replacement of the hornblende due to the inability of the biotite structure to accommodate titanium released from hornblende. Alternatively, the sagenite may result from sub-solidus exsolution of rutile from titaniferous biotite in response to changes in physical conditions which destabilized titanium in the biotite structure.

RELICT ASSEMBLAGE		AMPHIBOLITE FACIES ASSEMBLAGE
Quartz		Quartz increases
Calcic plagioclase		Plagioclase decreases
Orthopyroxene	Mg-Fe orthoamphibole	Non-sagenitic biotite
Clinopyroxene	Secondary hornblende	Non-sagenitic biotite
Biotite	Sagenitic biotite	Non-sagenitic biotite
Hornblende, Ilmenite, Spinel inclusions	Sagenitic biotite + Epidote	Non-sagenitic biotite
Minor K-feldspar		K-feldspar introduced

COMPOSITE ASSEMBLAGE

Quartz-Microcline-Oligoclase-Myrmekite-Sagenitic biotite-Secodary Hornblende Tertiary Biotite-Epidote-Zircon-Allanite-Sphene

RELICT : Orthopyroxene-Clinopyroxene-Primary Hornblende .

Table 3 . Paragenetic Development of the Uivak I Gneisses .

after Collerson and Bridgwater (1979) .

Fine-grained (0.1 mm maximum dimension) arrays of granular to prismatic epidote are noticeable in many rocks and bear a clear spatial association with the biotite-hornblende aggregates (Plate 25). In many instances, the epidote seems to be intergrown with the biotite, which suggests that they developed at the same time.

Collerson and Bridgwater (1979) have suggested that calcium released by hornblende breakdown reacted with Al-spinel inclusions and ilmenite to form epidote. Iron, magnesium and titanium were incorporated into biotite. The common association and intergrowth of epidote with biotite which formed at the expense of hornblende appears to support this hypothesis.

A small number of samples appear to retain orthopyroxene and clinopyroxene-bearing assemblages typical of the granulite facies. Orthopyroxene defines a foliation in these rocks and is associated with blue-green hornblende and reddish biotite, with which it appears to be in microstructural equilibrium. The orthopyroxene is partially or completely replaced by fibrous ortho-amphibole in most cases, and the amphibole is itself replaced by biotite. Collerson and Bridgwater (1979) have studied rocks which retain granulite facies assemblages and report similar assemblages and retrograde reactions linking these rocks to the more abundant amphibolite facies gneisses. Table 3 (taken from Collerson and Bridgwater, 1979) summarizes the paragenetic development of the Uivak I gneisses and is applicable to the rocks examined in this study.

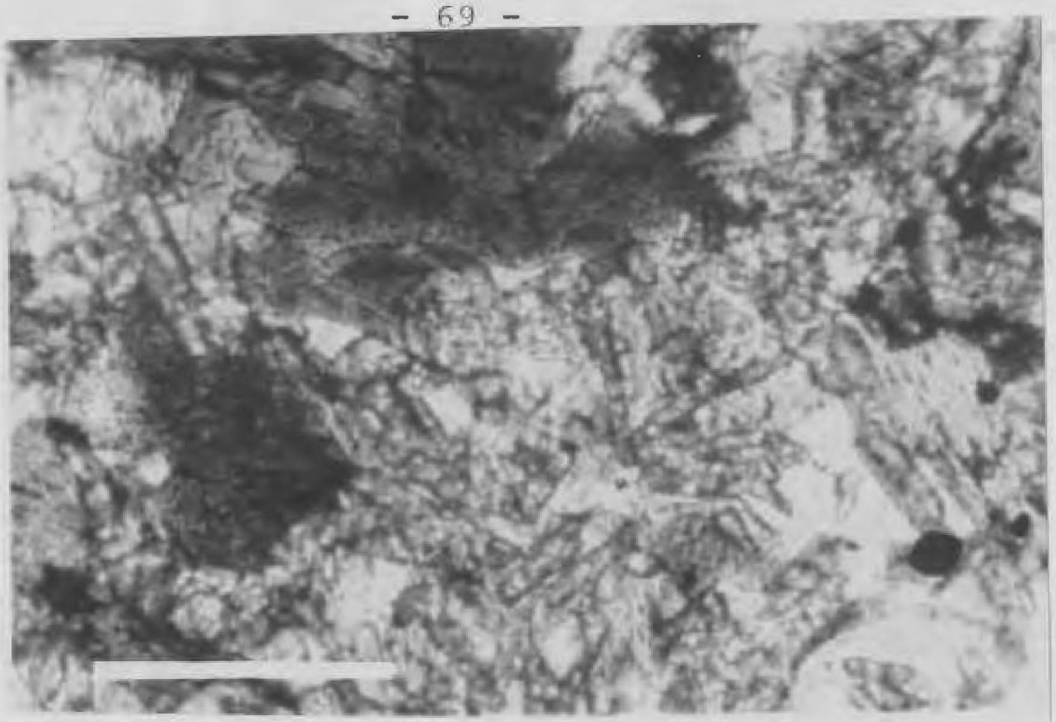


Plate 25 . Fine-grained prismatic epidote associated with biotite-hornblende aggregate .
Plane polarised light . Scale bar 0.3 mm .

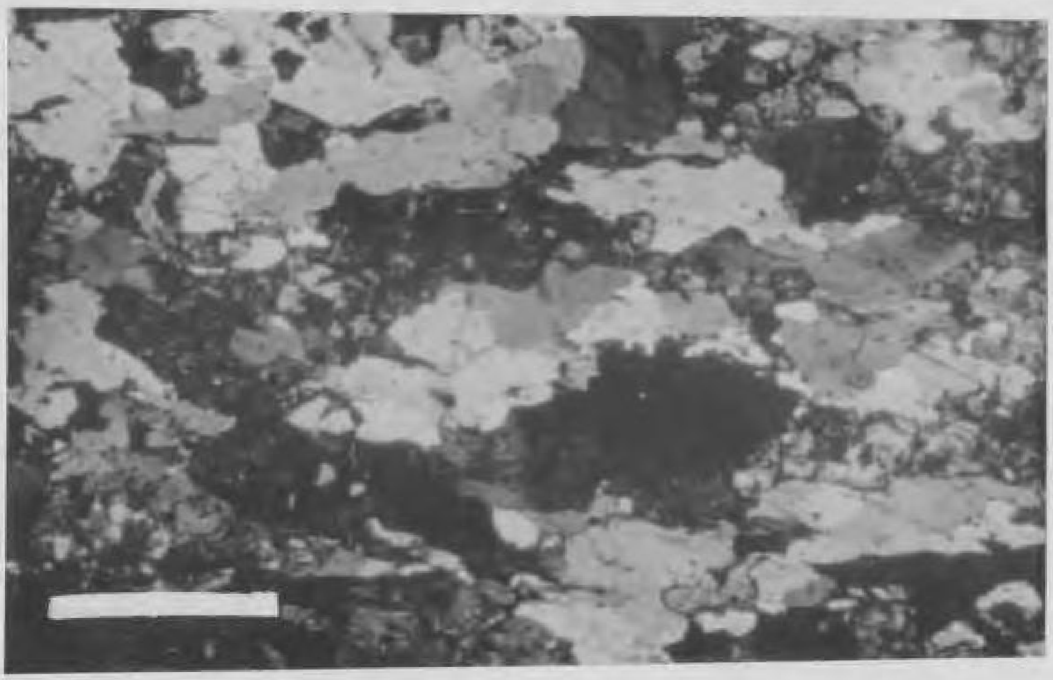


Plate 26 . Elongated amoeboid quartz grains ("ribbon quartz") in a porphyroclastic Uivak II gneiss .
Crossed nicols . Scale bar 1 mm .

4.2.2. Uivak I Layered Gneisses ("Migmatites")

The compositionally layered Uivak I gneisses are best considered in terms of two components, for which the terms leucosome and melanosome are used in a descriptive sense.

The melanosome is similar in all respects of the grey gneisses described in 4.1.2. and will not be described in detail here. It is generally very heterogenous in thin section and contains significant quantities of microcline. Only very rarely is the melanosome microcline free, and the foliation within it is usually much more pronounced than in the more homogenous gneisses described in the previous sub-section.

The pegmatitic leucosome is much coarser grained than the melanosome, with average grain sizes for most constituents falling between 2 and 4 mm. It is mineralogically comparable to the melanosome, but contains little or no biotite or hornblende and is generally richer in microcline.

Quartz is again visible as large, strained amoeboid grains and aggregates of small, polygonal strain-free grains. Plagioclase is present as large (2-4 mm) grains with faded, bent albite twin lamellae and strongly undulose extinction. In terms of composition, it is identical to the plagioclase in the melanosome and the grey gneisses (An_{20} to An_{25}). Rims of more albitic composition (An_2 to An_5) occur on many grains. Estimates of composition were made by microprobe analysis.

The major difference between the leucosome and the melanosome is in the abundance of potash feldspar which may make up as much as 50% of the leucosome. More commonly, however, it makes up between 25% and 40%. It is invariably microcline and is present as fresh grains ranging in size from 0.5 mm to 3 or 4 mm. Cross-hatched twinning is ubiquitous and evidence of deformation is commonly present in the form of bent twin lamellae and undulose extinction. The microcline appears to be in microstructural equilibrium with other phases, although myrmekite commonly exists at plagioclase-microcline inteffaces. It is variably perthitic; the most common varieties are string, rod, patch and flame perthites (terminology after Spry, 1969).

In contrast to microcline within the melanosome, the K-feldspar in the leucosome is of a similar size range to the plagioclase and appears to have been a primary member of the assemblage which has subsequently been deformed and slightly recrystallized.

Biotite occurs in very small quantities (less than 2%) in the leucosome and is usually present as small flakes less than 0.5 mm in length. It does not usually define a prominent foliation but, where a preferred orientation is seen, it is invariably parallel to that defined by the coarser biotite in the melanosome. The biotite displays a pleochroism and composition similar to that within the melanosome.

4.2.3. Uivak II Gneisses

The Uivak II gneisses contain higher modal contents of both potash feldspar and mafic constituents (biotite and/or hornblende) than Uivak I gneisses of similar quartz content. They are not usually migmatitic.

The most common assemblage amongst members of the Uivak II siute is quartz + oligoclase + microcline + biotite $\pm$ hornblende. Normal accessory phases are Fe-Ti oxides, epidote, zircon, apatite, allanite and sphene. The most distinctive feature of the gneisses are the conspicuous megacrysts or porphyroclasts ("augen") of potash feldspar.

Under the microscope, the megacrysts or porphyroclasts are commonly seen to consist of equigranular polygonal aggregates of microcline, with individual grains averaging 5 mm in diameter. Grain boundaries within the megacrysts approach stable 120^{o} configurations. In a few instances, however, the porphyroclasts still consist of a single, strained crystal containing inclusions of quartz, plagioclase and biotite. Evidence of recrystallization to strain-free aggregates around the margins of such porphyroclasts is common place. In one example, what appear to be relict carlsbad twins are preserved, suggesting the former presence of orthoclase at higher temperatures.

The microcline megacrysts are commonly perthitic and display rod, flame and patch textures. Cross-hatched twinning is very well developed in most grains and is often bent, kinked and undulose in extinction, indicating considerable post-crystallization deformation.

In the less deformed members of the Uivak II suite, it is also possible to recognize groundmass microcline, which is present as small anhedral grains identical in most respects to their porphyroclastic counterparts. Both types of microcline are associated with bulbous myrmekite growths at plagioclase-microcline interfaces. In more highly strained Uivak II gneisses, the cataclastic disruption and recrystallization of the porphyroclasts renders distinctions between groundmass and megacryst feldspars equivocal.

The ultimate origin of the megacrysts is not known with certainty. They may be phenocrysts of magmatic origin, or, alternatively, they may have been products of metasomatism, as suggested by Mehnert (1968). However, whatever their origin, they are clearly pre-tectonic with respect to the fabric development in the gneisses.

Quartz and plagioclase are also important constituents of the gneisses and are similar in most respects to their counterparts in the Uivak I gneisses. Plagioclase is of a similar compositional range (An_{20} to An_{27}) but is generally somewhat coarser grained. Albite and pericline twinning is often kinked and bent and the grains display undulose extinction. Individual twins are often wedge-shaped and probably formed in response to deformation (c.f. Vance, 1961; Vernon, 1965).

Quartz is once again present in two forms, i.e. (1) large amoeboid grains with serrated or embayed grain boundaries and (2) polygonal aggregates of small strain-free grains. The second variety is often observed as inclusions within the amoeboid grains, together with groundmass microcline of a similar size range. In sections cut parallel to the L or L-S fabrics in the gneisses, the interlocking amoeboid grains form prominent quartz "ribbons" (Plate 26). Boundaries between amoeboid quartz grains are usually serrated or embayed.

The dominant mafic phase is biotite which is pleochroic from pale yellow (X) to green-brown or dark brown (Y = Z). It is variably sagenitic and contains inclusions of zircon and allanite, which are surrounded by pleochroic haloes. In the least deformed members of the suite, biotite is present as large (up to 4 or 5 mm) crystals which are associated with a dark green pleochroic hastingsitic amphibole. In some cases the biotite appears to be in equilibrium with the amphibole whereas in other examples it shows a replacement relationship similar to that described from the Uivak I gneisses. In these instances, the sagenitic biotite is associated with fine-grained epidote, suggesting a similar hornblende breakdown reaction to that in the Uivak I suite.

4.3. THE KIYUKTOK GNEISSES

4.3.1. Kiyuktok Components of Intrusive Origin

Kiyuktok gneisses of "intrusive" origin are those which are characterized by the presence of a coarse, pegmatitic

Kiyuktok component which has been injected into the parent Uivak gneiss from elsewhere. In thin section, they are mineralogically simple and the most common assemblage is quartz + plagioclase + microcline + biotite ± relict garnet and/or orthopyroxene. Accessory minerals include epidote, apatite, zircon and allanite.

Most of these rocks display a fairly equigranular granoblastic mosaic of quartz, plagioclase and microcline (Plate 27). Average grain sizes are variable, but generally fall between 1 and 4 mm, with an upper limit of 7 or 8 mm. There does not appear to be any relationship between grain size and the size of sheets and veins of Kiyuktok component.

Quartz grains commonly occur in clusters with a similar optical orientation, suggesting that they are amoeboid in shape. They are variably strained; in the finer-grained rocks they tend to be virtually strain-free, but those in coarse-grained varieties display pronounced deformation bands and display strongly undulose extinction. In some examples, this sub-grain structure has developed to the extent where the edges of the grain recrystallize to polygonal aggregates of small (0.1-0.2 mm) strain-free grains.

Grain boundaries between quartz grains and other phases are of variable appearance; they range from straight through curved to embayed and serrated (terminology after Spry, 1969).

Plagioclase is present in variable amounts but is usually subordinate to K-feldspar. Compositionally, it is

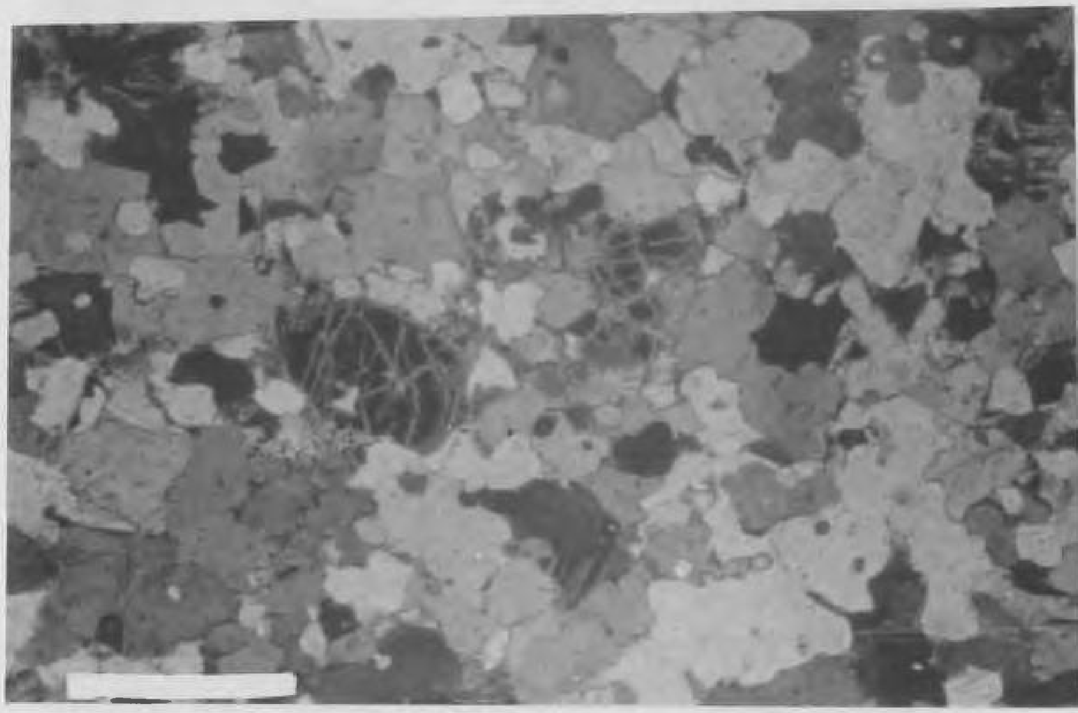


Plate 27 . Equigranular granoblastic mosaic of strain-free grains in a garnetiferous Kiyuktok pegmatite .
Crossed nicols . Scale bar 1 mm .

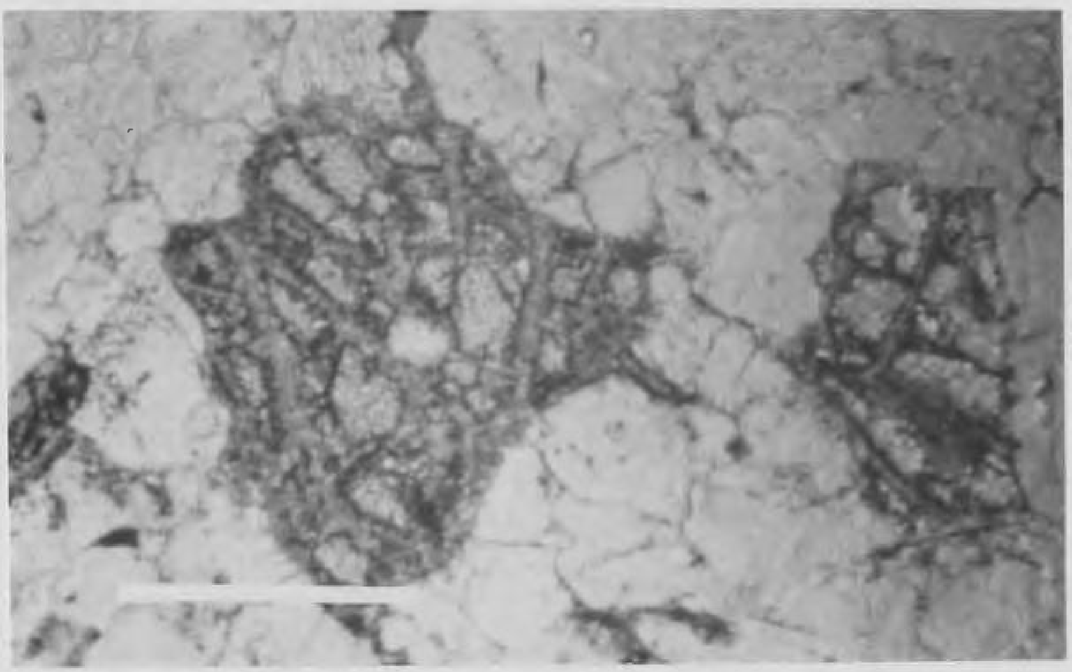


Plate 28 . Relict garnet with a replacement rim of fine grained green biotite .
Plane polarised light . Scale bar 1 mm .

an oligoclase ranging from An_{18} to An_{27} (estimates by optical methods and electron microprobe analysis). This compositional range is comparable to that of plagioclase in the Uivak gneisses. Its normal mode of occurrence is as fresh, subhedral grains which normally lack well-defined albite twin lamellae and display slightly undulose extinction.

A more sodic variety of plagioclase (An_1 to An_5) is also present in the Kiyuktok gneisses and occurs both as rims upon earlier oligoclase and as discrete, sharply twinned grains up to 1 mm in diameter.

Microcline is the most abundant feldspar and usually makes up between 40 and 75% of the feldspars. It is fresh, sharply twinned, invariably perthitic and present as fresh, subhedral to anhedral grains which are commonly larger than either quartz or plagioclase. Grain boundaries between microcline and other phases are generally straight to curved and interfacial angles approach 120^{o} configurations in places. Wart-like myrmekite growths are frequently developed at interfaces with plagioclase.

The mafic minerals in the Kiyuktok pegmatites are almost entirely concentrated in glomeroporphyroblastic aggregates (or "clots") ranging in diameter from less than 1 mm to over 10 mm. Most of the clots are composed of green biotite, epidote and a pinkish garnet. Garnet is preserved in the central parts of the blebs and is replaced by intergrowths of biotite and epidote (Plate 28).

A moderately pleochroic brown biotite (X = pale yellow, Y = Z = medium brown) is also present in smaller quantities in intrusive Kiyuktok components, where it forms small (3-4 mm) "clots" which are composed of decussate aggregates of small (0.5 mm to 1 mm long) flakes. The pleochroism of this biotite is much less intense than that in the Uivak gneisses and it is not visibly sagenitic. Typical analyses of garnets and biotites from Kiyuktok pegmatites are shown in Table 4.*

Some of the intrusive Kiyuktok pegmatites contain fibrous aggregates of orthorhombic amphibole which are partly replaced by biotite. Similar fibrous growths are seen to replace orthopyroxene in Kiyuktok nebulites (4.3.3.) and also in the Uivak I gneisses (4.2.1.). By analogy with these examples, orthoamphibole in the pegmatites is regarded as an alteration product of orthopyroxene. Collerson (pers. comm.) has observed relict orthopyroxene in Kiyuktok pegmatites at Torr Bay, which lends further support to this argument. Fresh orthopyroxene is recorded from one pegmatite at Kiyuktok Cove (Plate 29) where it is altered to a fibrous orthoamphibole.

4.3.2. Kiyuktok Components of In-Situ Origin

These are similar in some respects to the intrusive pegmatites described in the previous sub-section. However, there are some important differences between the two types of Kiyuktok component.

*See Appendix.

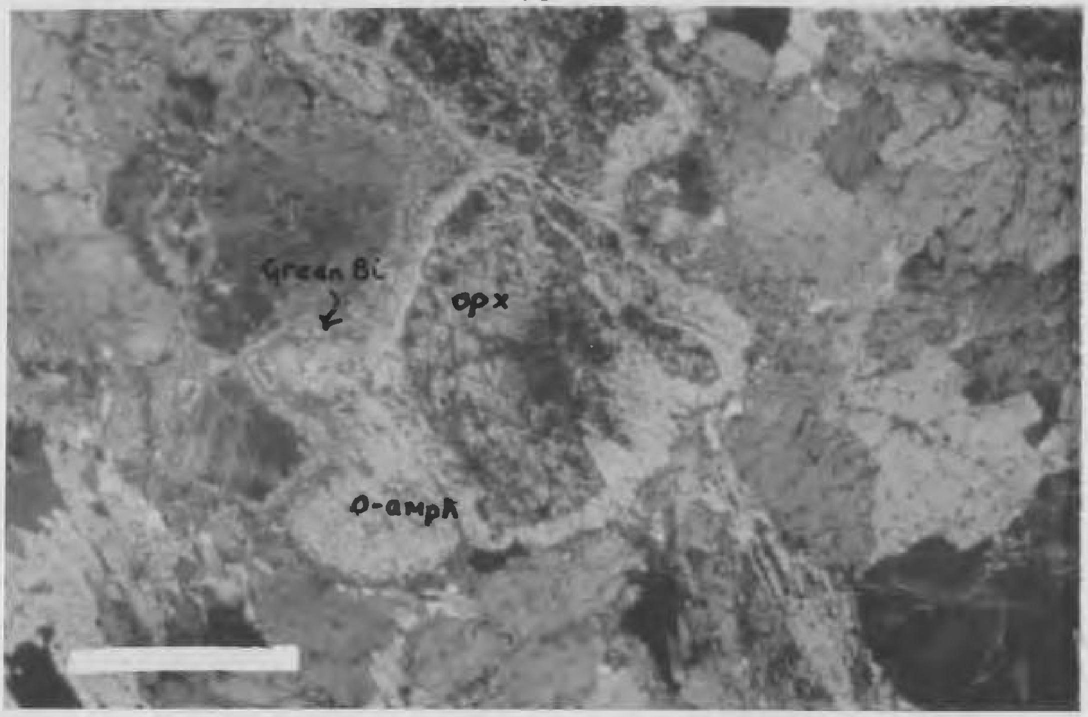


Plate 29 . Relict orthopyroxene (centre) replaced by fibrous ortho-amphibole and green biotite .
Crossed nicols . Scale bar 1 mm .

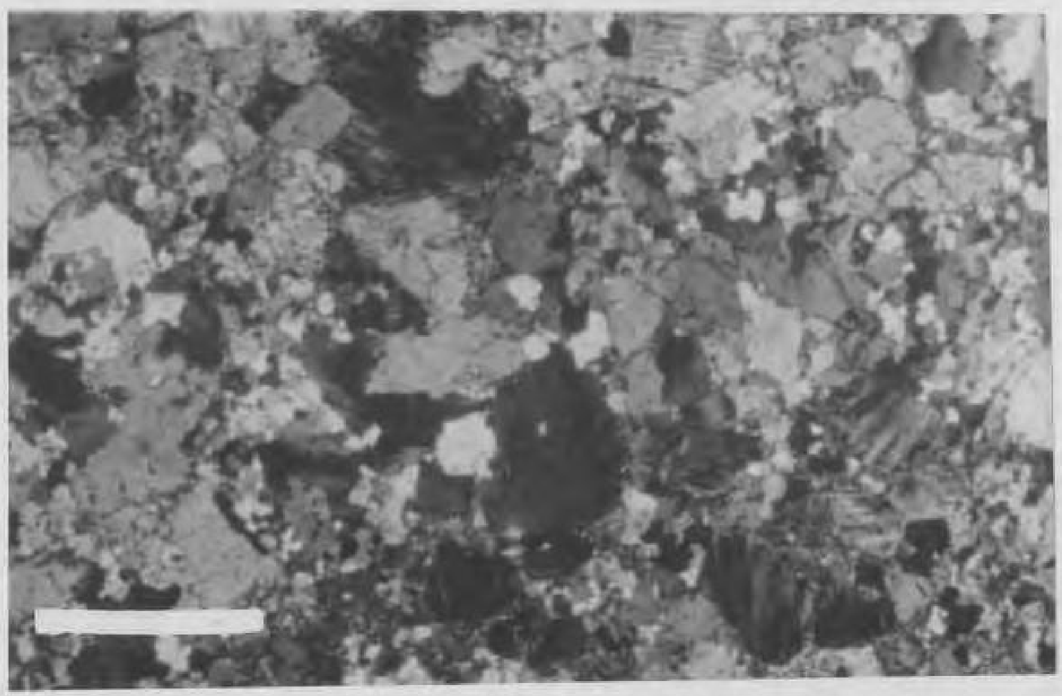


Plate 30 . Strongly inequigranular Kiyuktok gneiss formed by <u>in situ</u> reconstitution of a Uivak I gneiss . The fine-grained zones are interpreted as loci of melt formation
Crossed nicols . Scale bar 1 mm .

The most noticeable feature of the Kiyuktok components which formed in place is an overall heterogeneity caused by a great variation in the size of quartz, plagioclase and microcline. Fine-grained polygonal areas composed largely of quartz, with smaller amounts of plagioclase and microcline are very prominent and are distributed fairly regularly through the gneisses (Plate 30). The size of these fine-grained domains is quite variable; they range from less than 1 mm in diameter to up to 10 mm across in places. The average grain size within these domains is approximately 0.1-0.3 mm. The total amount of fine-grained material in the gneisses is normally less than 10% by volume.

The coarser-grained portion of in situ Kiyuktok components is composed essentially of the same three minerals, but the proportions of individual phases are rather different. Most of the larger grains are plagioclase of a similar compositional range (An_{18} to An_{25}) to that in the Uivak gneisses (estimates by optical methods and electron microprobe analysis). These large plagioclase grains are also morphologically similar to those in the Uivak gneisses; they do not display a well-defined albite twinning and they show strongly undulose extinction. They contrast sharply with the plagioclase in the fine-grained domains, which is more sodic (An_2 to An_6) and occurs as sharply twinned, strain-free grains.

Quartz is present in both domains. In the coarser domains it occurs as large, strained grains with a prominent sub-grain structure. In many examples, several individual grains show a common optical orientation, suggesting a complete three-dimensional shape similar to that of the amoeboid quartz grains in the Uivak gneisses. The amoeboid character of the quartz is not as striking in the Kiyuktok gneisses because of extensive replacement by fine-grained material around the edges of the original amoeboid grains.

Microcline is much less abundant in in situ Kiyuktok components than in intrusive varieties. It is present in both fine-grained and coarse-grained areas, but is most commonly present as a fine-grained phase associated with polygonal quartz and albitic plagioclase. It is present as variably perthitic polygonal grains with prominent twinning which display curved to straight interfaces against other phases.

In situ Kiyuktok components are richer in biotite than their intrusive counterparts. The biotite is a moderately pleochroic variety ranging from pale yellow (X) to brown or deep olive green (Y = Z). It is sagenitic in places but does not display the intense pleochroism of the Fe-rich Uivak biotites. It is concentrated into irregular clots ranging up to 7 or 8 mm in diameter. Within the clots, biotite is present either as well-formed crystals up to 3 x 1 mm in size or as lepidoblastic to decussate aggregates composed of tiny flakes whose length is usually less than 0.1 mm.

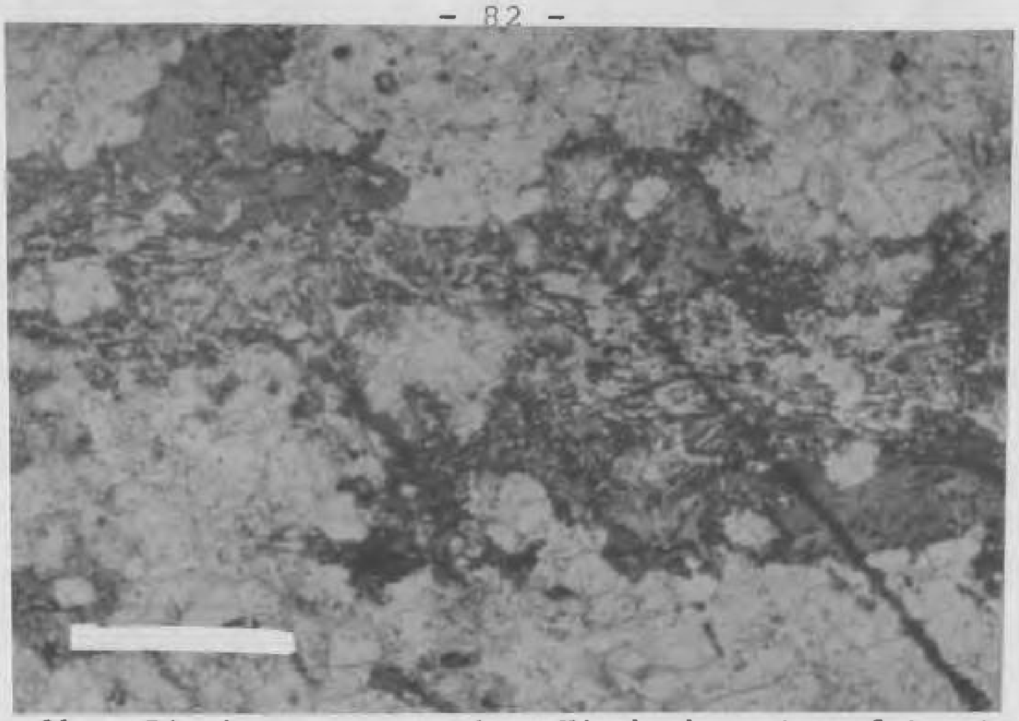


Plate 31 . Biotite aggregate in a Kiyuktok gneiss of in situ origin . Note radiating crystals and graphic biotite-quartz intergrowths .
Plane polarised light . Scale bar 1 mm .

Plate 32 . "Graphic" biotite in a nebulitic Kiyuktok gneiss .
Plane polarised light . Scale bar 0.5 mm .

Within these aggregates, biotite is frequently intergrown with fine-grained quartz and occurs as numerous flakes which share a common optical orientation (Plate 31). These biotite-quartz intergrowths are referred to as "graphic" biotites and appear to be a characteristic feature of in situ Kiyuktok components. A colourless, fibrous orthoamphibole is sometimes observed in the central parts of aggregates of graphic biotite which appear to be replacing it.

Relict garnet has only rarely been observed in Kiyuktok gneisses of in situ origin. Where present, it is found in the central portions of the clots where it is replaced by green biotite, epidote and quartz in a manner comparable to that observed in intrusive Kiyuktok pegmatites.

4.3.3. Kiyuktok Gneisses of Uncertain Origin (Nebulites)

It is only possible to discriminate between the "intrusive" and "in situ" development of the Kiyuktok gneisses in areas where the reworking of the Uivak gneisses was incomplete. Most of the Kiyuktok gneisses are products of extensive remobilization and original relationships between the Kiyuktok and Uivak components are no longer preserved.

These "nebulitic" rocks bear more resemblance to the intrusive pegmatites than to those Kiyuktok components which formed in place. They are fairly homogeneous rocks consisting of an equigranular to slightly inequigranular mosaic of quartz, plagioclase and microcline. Quartz is relatively strain-free in most examples and consists of rounded grains up to 1 or 2 mm across which probably have a complex amoeboid shape in three dimensions. Most of the plagioclase is a strained, faintly twinned oligoclase (An_{18}-An_{25}) similar to that in the Uivak gneisses and the in situ Kiyuktok components.

Microcline is an important constituent but is less abundant than in clearly intrusive varieties. It is of a similar size range to quartz and plagioclase and is fresh, well-twinned and variably perthitic.

The mafic minerals are concentrated into "clots", but these are not as well defined as in intrusive varieties. In Kiyuktok gneisses which were affected by post-crystallization deformation, the clots are elongated and collectively define a foliation which may or may not be parallel to the layering within the Uivak gneisses. The "clots" are composed mostly of green or green-brown biotite, but a number of relict minerals occur in the interior portions of the aggregates.

Garnet is a fairly common constituent and, as in Kiyuktok gneisses of known origin, is replaced by green biotite and epidote. It is accompanied in some examples by rounded, irregular grains of a mineral which is believed to be orthopyroxene. Where least altered, this possesses a prominent length-slow prismatic cleavage, a moderate birefringence (0.01 - 0.014) and straight extinction. Determinations of optical sign are difficult due to alteration, but it appears to be biaxial negative with a large 2V. These optical characteristics and the composition of the mineral (Table 3) are consistent with those of orthopyroxene.

In most cases, the orthopyroxene is altered to fibrous aggregates of colourless orthoamphibole which are rimmed by "graphic" brown biotite-quartz intergrowths similar to those in the *in situ* Kiyuktok components, but significantly coarser grained (Plate 32). Similar aggregates of fibrous orthoamphibole are also present in some of the Uivak gneisses (see 4.2.1.) and are also regarded as alteration products of orthopyroxene.

In Kiyuktok gneisses which do not retain relict garnet or orthopyroxene, graphic brown biotite-quartz intergrowths are usually present and suggest the former presence of orthopyroxene. Very fine-grained aggregates of green biotite and epidote are present in some rocks, which may indicate the former presence of garnet.

4.3.4. The Uivak Component in Kiyuktok Gneisses

The Uivak component in the Kiyuktok gneisses is macroscopically indistinguishable from Uivak gneisses which were not affected by reworking. In rocks which were only moderately affected (i.e. those containing less than about 20-30% Kiyuktok component), the Uivak component retains most of microstructural features which are reviewed and discussed in section 4.2.4.

However, in the extensively reworked rocks which dominate the Kiyuktok gneisses, the Uivak component has been modified to some extent. This modification is expressed in a number of different ways.

In Kiyuktok gneisses which have developed via the emplacement of pegmatitic material without widespread in situ reworking, the relict Uivak component often exhibits an "annealed" appearance. This is expressed by an equigranular granoblastic mosaic of quartz, plagioclase and microcline which seems to be in complete microstructural equilibrium. All of the quartz is in the form of variably strained amoeboid grains.

In Kiyuktok gneisses which suffered extensive in situ transformation, the relict Uivak component is comparable in many respects to the in situ Kiyuktok component which is believed to have developed from it.

It is rather heterogeneous in thin section and displays coarse and fine-grained domains similar to those in the Kiyuktok component (4.3.2 and Plate 30), but with a smaller proportion of fine-grained material. The fine-grained domains consist of quartz, microcline and sodic plagioclase (An_2 to An_7) and are thus distinct from the fine-grained domains in unreworked Uivak gneisses, which consist only of quartz and microcline.

The spatial relationships of the coarse and fine-grained domains also contrast with those in unreworked Uivak gneisses. In the latter, fine-grained domains are preserved only as relics within and between large amoeboid quartz grains with serrated boundaries. This relationship seems to be reversed in areas where the gneisses were reworked; here the larger, strained grains are <u>rimmed</u> by the fine-grained domains and boundaries between the two are straight in most cases. The possible significance of these relationships will be discussed in Chapter 5.

The Uivak component in these examples seems to be transitional in appearance between unreworked Uivak gneisses similar to those described in 4.2 and in situ Kiyuktok components like these described in 4.3.2. In thin section, it is impossible to define boundaries between the "Uivak" and "Kiyuktok" components. Transitions between the two are completely gradational and are characterized by increasing heterogeneity (i.e. an increase in the proportion of fine-grained material) and an increase in modal microcline. The amount of biotite remains relatively constant throughout, although it is concentrated into clots within the Kiyuktok component and often forms graphic intergrowths with quartz. These "graphic" biotites are sometimes present within the Uivak component, but are usually only small-scale features.

4.4. THE IKARUT GNEISSES

In thin section, the Ikarut gneisses range from slightly deformed rocks which are clearly of intrusive origin to extensively recrystallized gneisses displaying strong fabrics. The least deformed examples are described first, since they represent the closest approach to the protoliths and have a strikingly "igneous" appearance (Plate 33).

The most common mineral assemblage amongst members of the Ikarut suite is quartz-plagioclase-microcline-biotite $\pm$ hornblende. Normal accessory constituents are Fe-Ti oxides, apatite, sphene and zircon. Plagioclase is normally dominant over microcline, which is absent in some of the more mafic varieties. Some of the adamellitic and granitic Ikarut gneisses do, however, contain significant quantities of microcline.

Plagioclase is normally the most prominent constituent and ranges in composition from An_{32} to An_{40} (andesine). Evidence of some post-crystallization deformation is present in the form of bent twinning and undulose extinction, and wedge-shaped twins are prominent in some examples. In the strongly porphyritic rocks, plagioclase is present both as large, euhedral phenocrysts up to several millimeters across and as small, subhedral to anhedral grains in the groundmass.

Quartz is present in variable amounts (5-25%) and is normally present as small, anhedral to polygonal grains up to 0.5 mm across. In strongly porphyritic examples, it forms interstitial domains up to 5 or 6 mm across where it is associated with small amounts of plagioclase and/or microcline. Undulose extinction and sub-grain structure are prominent in some grains. Grain boundaries between quartz and other phases are normally straight to curved and display 120^{o} interfacial angles in some areas.

Microcline feldspar is present in most of the rocks, but is usually only a minor constituent which occurs as small anhedral grains in the groundmass. In some of the quartz-rich granitic Ikarut gneisses, microcline is more abundant and frequently occurs both as large phenocrysts and within the groundmass. The microcline is frequently perthitic and is characterized by myrmekitic growths at its interfaces with plagioclase.

Biotite is the dominant mafic phase, and is sometimes associated with smaller quantities of dark green, pleochroic hastingsitic amphibole. The biotite is an intensely pleochroic variety similar to that in the Uivak gneisses, but only rarely sagenitic. Where amphibole is present, it is invariably replaced by the biotite, which is itself overgrown by white mica in places. In some of the least deformed Ikarut gneisses, biotite is present as euhedral plates up to 2 or 3 mm in places. The deformed varieties usually contain lepidoblastic aggregates in place of single crystals. Fine-grained epidote is associated with biotite-hornblende aggregates in some rocks, suggesting that hornblende breakdown took place by a mechanism similar to that inferred for the Uivak gneisses (section 4.2.1.).

In the more deformed Ikarut gneisses, it becomes much more difficult to recognize the igneous textures which are

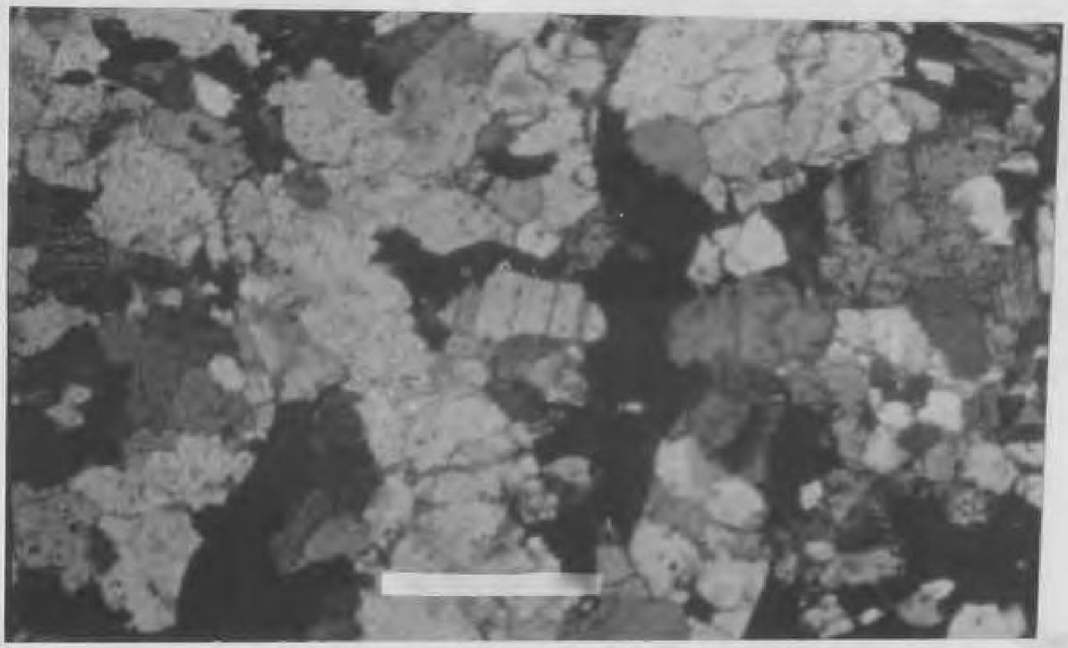


Plate 33 . Relatively undeformed Ikarut gneiss . Note well-twinned plagioclase and equigranular granoblastic mosaic . Crossed nicols . Scale bar 1 mm .

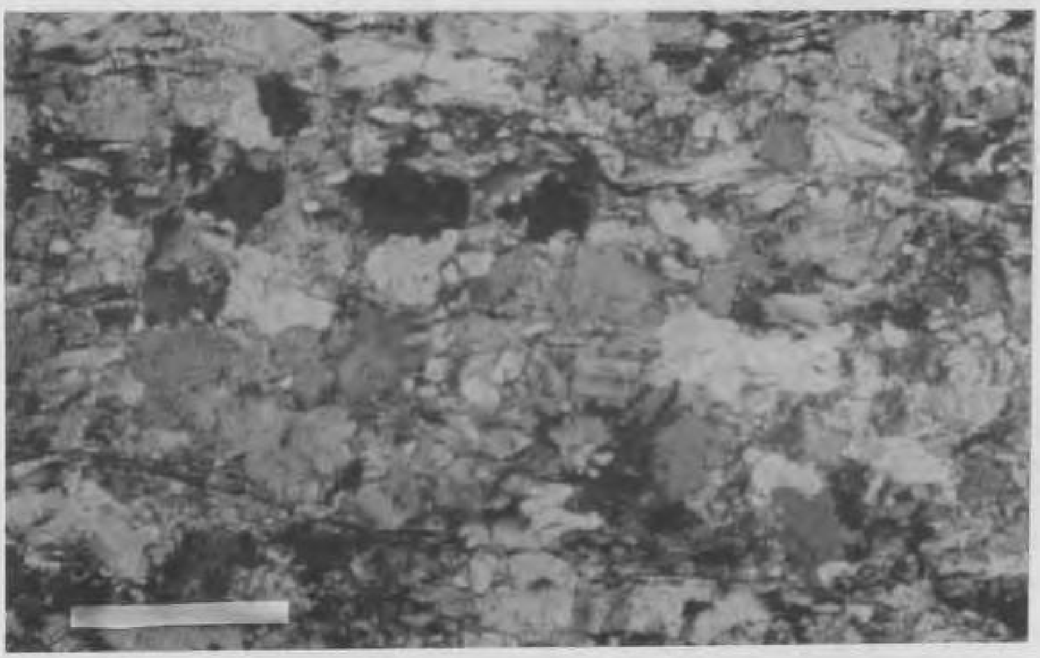


Plate 34 . Extensively recrystallised Ikarut gneiss with K-feldspar porphyroclasts and protomylonitic fabric .

Crossed nicols . Scale bar 1 mm

described above. In non-porphyritic Ikarut gneisses quartz and feldspar become increasingly strained and some recrystallization of quartz to very fine-grained polygonal aggregates takes place. A noticeable elongation of quartz and feldspar is also noticeable and this is parallel to a strong foliation which is defined by lepidoblastic aggregates of biotite ranging up to 2 or 3 mm in length.

The porphyritic varieties develop spectacular porphyroclastic fabrics with increasing deformation. These are characterized by rounded augen of plagioclase (and microcline in more felsic rocks) which are enclosed in a very fine-grained recrystallized groundmass consisting largely of quartz (Plate 34). The augen are extensively fractured in some examples and these fractures are occupied by fine-grained quartz.

Some areas of coarser-grained quartz are visible. These consist of irregular, elongate grains which often show comparable optical orientation. They are interpreted as products of secondary recrystallization (exaggerated grain growth) and are believed to represent incipient quartz ribbons analogous to those developed in the Uivak II augen gneisses (4.2.3.).

Biotite in the porphyroclastic gneisses occurs as lepidoblastic aggregates of small (<0.2 mm long) grains which are aligned parallel to the porphyroclastic fabric and which wrap around augen of plagioclase and/or microcline. Hornblende is only rarely present.

There seems little doubt that the Ikarut gneisses are derivatives of a suite of equigranular to porphyritic igneous rocks ranging from diorites to quartz-diorites, tonalites and granodiorites, with subordinate granitic rocks. It is clear that they do not have a complex polyphase history comparable to that of the Uivak and Kiyuktok gneisses and they are almost certainly a relatively late-stage component of the gneiss complex.

CHAPTER 5

QUARTZOFELDSPATHIC GNEISSES -- DISCUSSION AND INTERPRETATION

5.1. INTRODUCTION

Although two additional groups of gneisses have yet to be described and structural geology remains to be discussed, it is logical at this point to discuss the field relations and petrology of the Quartzofeldspathic gneisses in more detail.

Topics of particular emphasis in this chapter are (1) the origin of Uivak gneisses, (2) the development of the Uivak gneisses in response to later deformation and metamorphism, and (3) the development of the Kiyuktok gneisses. The last topic is discussed in some detail to provide a framework for a model which is presented in the final chapter.

5.2. THE ORIGIN OF THE UIVAK GNEISSES

There appears to be fairly convincing field evidence indicating that the Uivak gneisses are complex polyphase derivatives of plutonic igneous rocks.

In a few small enclaves which escaped the full effects of later deformation and metamorphism, the Uivak I gneisses are homogeneous, medium-grained trondhjemitic, tonalitic and granodioritic rocks. Intrusive relationships between different phases of the Uivak I protoliths are preserved in these areas and xenoliths of the earliest supracrustal rocks (the Nulliak assemblage) occur in places. Outside of these areas, the Uivak I gneisses are strongly foliated and layered "migmatitic" rocks, but the melanosome is lithologically comparable to the more homogeneous varieties. The progressive development of the layering in the Uivak I gneisses can be documented in a few areas; this is something of a problem in itself and will be discussed more fully in the next section.

In the case of the Uivak II gneisses, field evidence for derivation from porphyritic granodiorites and adamellites is unequivocal. In areas of low intensity deformation (such as the central part of the Fire Cove belt, Mentzel Island and Maidmonts Island), they retain spectacular megacrystic textures and display intrusive relationships with the Nulliak assemblage and the Uivak I gneisses. The development of the more strongly deformed cataclastic varieties can be traced along the margins of these enclaves.

In recent years, a number of geochemical studies of early Archean gneisses have been carried out in an attempt to clarify the origin of these rocks. The difficulties involved in the interpretation of petrological and geochemical data from high-grade gneiss complexes is perhaps best illustrated by the wide range of conclusions reached by various workers. Early Archean quartzofeldspathic gneisses have been interpreted as metagreywackes (Kalsbeek, 1970; Holland and Lambert, 1975); metavolcanics (Sheraton, 1970; Bowes et al., 1971; Bowes and Hopgood, 1975) and as derivatives of plutonic rocks (McGregor, 1973; Bridgwater and Collerson, 1976; Collerson et al., 1976). In a general sense, Early Archean gneisses are compositionally similar to all three groups of rocks, but in detail they do not compare strictly with any of them. The most distinctive feature of these rocks is a wide variation in their contents of large-ion-lithophile (L.I.L.) elements such as K, Na, Rb, Ba and Sr. In terms of major element composition, they are similar to their postulated igneous protoliths and appear to show a calc-alkaline trend (Collerson and Bridgwater, 1979). Tarney (1976) has reviewed some of the problems of origin and concludes that the most likely protoliths to Early Archean gneisses are calc-alkaline intrusive rocks.

Whilst this may well be the case, the great variation in L.I.L. element concentrations, and their extreme depletion in granulite facies rocks (e.g. Drury, 1973; Lewis and Spooner, 1972; Heier, 1973; Collerson and Fryer, 1978) suggests that allochemical processes are involved in high-grade metamorphism. Geochemical observations cannot, therefore, be regarded as conclusive evidence, but they do appear to support field observations which suggest that the Uivak gneisses were derived from plutonic igneous rocks.

5.3. THE DEVELOPMENT OF THE UIVAK I "MIGMATITIC" GNEISSES

Throughout the study area, and over most of the Saglek-Hebron area, the Uivak I gneisses are represented by strongly layered "migmatitic" rocks which do not resemble intrusive igneous rocks in any way. It is, however, possible to trace layered gneisses laterally into more homogeneous gneisses, which suggests that the two groups are closely related.

Field evidence strongly suggests that the layering in the Uivak gneisses is largely a product of repeated intense deformation. In areas where their igneous character is well preserved, the Uivak I gneisses are cut by irregular quartz-microcline-plagioclase pegmatites. These pegmatitic patches are in turn cut by both Uivak II gneisses and Saglek dykes, which suggests that they are an early feature of the gneiss complex.

When the gneisses are traced away from these enclaves of low intensity deformation, the pegmatites are progressively attenuated and re-oriented by folding until a discontinuous layering is produced. Evidence of the disruption of the pegmatites is preserved only in the form of rootless, intra-folial folds which are a ubiquitous feature of the Uivak I layered gneisses. The development of a migmatitic layering by the deformation and disruption of pegmatites is shown schematically in Fig. 6. A similar origin has been proposed for layered gneisses in the Hebron area by Ryan (1977) and comparable mechanisms are documented by Myers (1970, 1978) from Archean terrains in Scotland and West Greenland.

The ultimate origin of the K-feldspar-rich pegmatites from which the layering was produced is debatable. They may

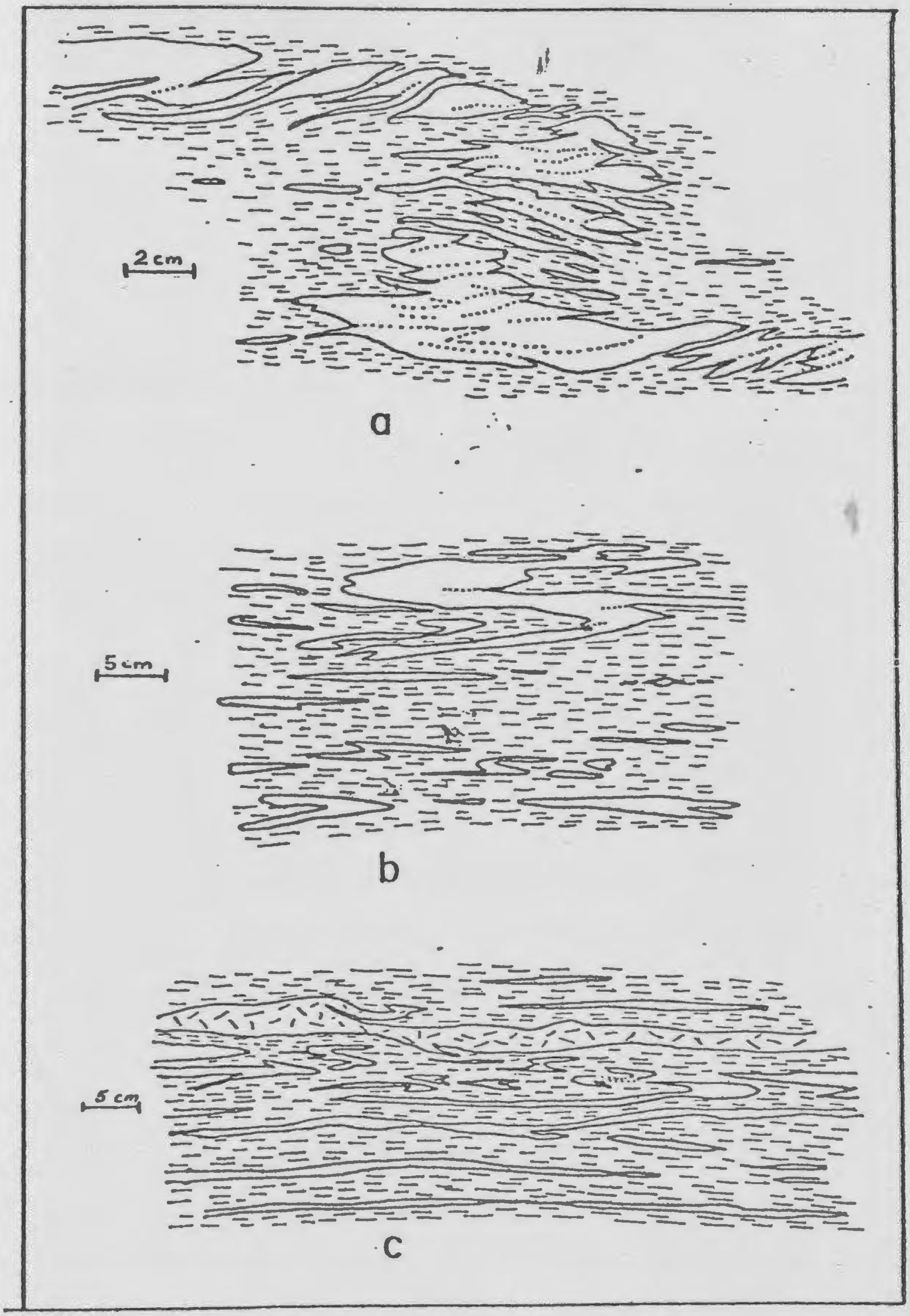


Figure 6 . Schematic Diagram showing the progressive disruption and attenuation of pegmatite segregations in the Uivak gneisses to produce a migmatitic layering . Cross-hatched pattern in (c) represents a later pegmatite . Drawing courtesy of A.B.Ryan .

have been injected into the Uivak gneisses from elsewhere, or produced in situ by either partial melting or hydrothermal processes such as metamorphic segregation. When plotted on a normative Qz-Ab-Or diagram, the pegmatites show compositions which are close to those of a minimum melt in the system Qz-Ab-Or-H_2O with excess H_2O (Collerson and Bridgwater, 1979). This suggests that they may have been derived via partial melting, although the problems of external and internal derivation remain. Plagioclase compositions within melanosome and leucosome are, however, identical which, according to Yardley (1978), is suggestive of metamorphic segregation rather than anatexis, which would produce significantly more Ab-rich plagioclase.

This similarity in plagioclase composition may, however, be related to later periods of hydrothermal activity which affected a leucosome formed initially by anatexis. Indeed, both isotopic evidence (Hurst et al., 1975; Bridgwater and Collerson, 1976) and microstructural evidence (section 5.4) suggests that there was an influx of potassium and rubidium which affected the Uivak I gneisses circa 3,600 Ma ago. The leucosome was already in existence before this influx and some fluid-assisted redistribution of Ca and Na may have buffered plagioclase compositions at this time. The scattered occurrence of early granulite facies assemblages in Uivak I gneisses (Collerson and Bridgwater, 1979) suggests that high-grade metamorphic conditions sufficient for anatexis were attained at an early stage in the evolution of the complex.

5.4. METAMORPHIC AND MICROSTRUCTURAL DEVELOPMENT OF THE UIVAK GNEISSES

Field evidence from areas of anomalously low intensity deformation (see section 3.5) strongly suggests that the Uivak gneisses are complex polymetamorphic derivatives of a composite suite of intrusive rocks. Rocks from these areas, although obviously metamorphic in character, can reasonably be assumed to represent the closest approach to the early characteristics of the Uivak suite.

A number of small areas within the Uivak gneisses preserve evidence of granulite facies assemblages containing orthopyroxene, clinopyroxene and hornblende as stable mafic phases. These are variably retrogressed to form the more widespread biotite-bearing assemblages. These granulite facies assemblages are also regarded as early features of the Uivak suite which are only sporadically preserved.

It is interesting and informative to compare these relics of earlier igneous and metamorphic episodes with the more widespread amphibolite facies layered gneisses which are typical of the Uivak suite throughout the Saglek-Hebron area.

Firstly, it is noticeable that those Uivak I grey gneisses from areas where igneous features are well preserved tend to be microcline-poor rocks of tonalitic or trondhjemitic affinities. Rocks which retain earlier granulite facies assemblages were studied by Collerson and Bridgwater (1979) and also contain little or no alkali-feldspar.

In thin section, gneisses from an exceptionally well-preserved area at Saglek Bight possess an equigranular granoblastic microstructure consisting of equant grains of strained quartz and plagioclase ranging up to 2 mm in diameter (Plate 35). Interfaces between the two phases are straight to curved and interfacial angles approach 120^{o} in many cases. Biotite is the principal ferromagnesian phase and is present as euhedral to subhedral laths which lack any well-defined systematic orientation.

Recrystallization of quartz does not appear to have been extensive in these rocks and the heterogeneity which characterizes many of the other Uivak gneisses in thin section is completely lacking.

The bulk of the Uivak I gneisses elsewhere in the area are markedly heterogeneous and display considerable evidence of recrystallization. Quartz is present as aggregates of small, polygonal strain-free grains and also as large, amoeboid grains which enclose the former. In many places these larger grains commonly have serrated boundaries against the smaller quartz grains. Microcline is an important constituent of many of these gneisses and is usually associated with areas where fine-grained quartz is present. Biotite in Uivak I layered gneisses is usually present in lepidoblastic

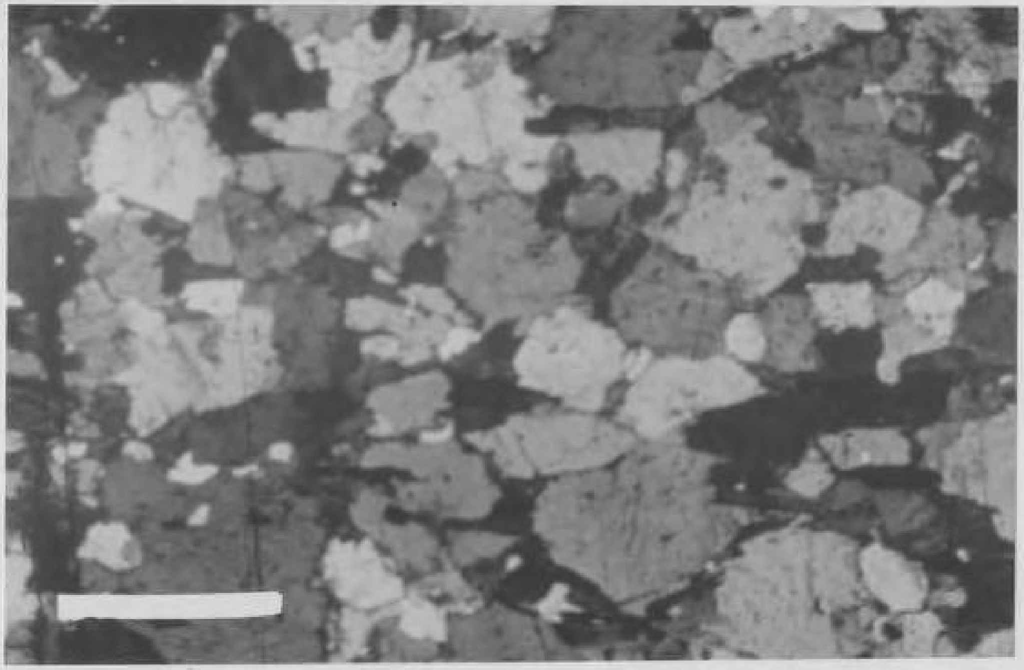


Plate 35 . Relatively undeformed Uivak I tonalite from Saglek Bight , Big Island . This is regarded as a close approach to the original (pre-3,600 Ma) characters of the Uivak I suite .
Note similarity to undeformed Ikarut gneiss shown in plate 33 .
Crossed nicols . Scale bar 1 mm .

aggregates of small (< 0.2 mm) flakes and associated with fine-grained epidote. Where hornblende is present, it is invariably replaced by sagenitic biotite and epidote.

Essentially the same features can be recognized in the leucocratic pegmatitic layers within the layered migmatitic gneisses, and also within the Uivak II gneisses, where extensive recrystallization of microcline feldspar megacrysts has also occurred.

These features are best envisaged as a result of two processes. The first stage in the development of these distinctive microstructures was the recrystallization of much of the quartz to an aggregate of small, polygonal strain-free grains. In most of the Uivak gneisses, this process went to completion and earlier strained quartz grains with prominent sub-grain structure are recognized only rarely. In the Uivak II gneisses, microcline megacrysts were substantially recrystallized to aggregates of smaller grains. The recrystallization of quartz in the Uivak I gneisses seems to have been accompanied by the introduction of microcline to the rocks, since this is intergrown with the fine-grained quartz.

The mafic minerals within the rocks also underwent some changes. Those rocks which retained earlier granulite facies assemblages were retrogressed to give hornblende-biotite bearing assemblages (see 4.1.2 and Collerson and Bridgwater, 1979). Further retrogression caused the breakdown of hornblende to sagenitic biotite and epidote.

Rocks which were initially biotite-bearing suffered some recrystallization of biotite to fine-grained aggregates. Sagenitic biotite developed at the expense of hornblende was similarly recrystallized.

This period of grain size reduction was followed by a period of grain growth which produced the large, amoeboid quartz grains which are a prominent feature of the Uivak gneisses. The most likely process to account for the development of these large grains is exaggerated grain growth or "secondary recrystallization" (Vernon, 1976). Secondary recrystallization involves the rapid growth of certain preferentially oriented grains in aggregates produced by earlier polygonization or "primary recrystallization". Once initiated by the coalescence of several grains of similar orientation, this process quickly produces large interlocking amoeboid grains. The serrated boundaries which these grains show against polygonal areas are also regarded as evidence of grain boundary migration (c.f. Spry, 1969) during the production of these large grains. The fact that they enclose areas of polygonal quartz and microcline, and, in places, sagenitic biotite, indicates that secondary recrystallization was a late event in the microstructural evolution of the rocks.

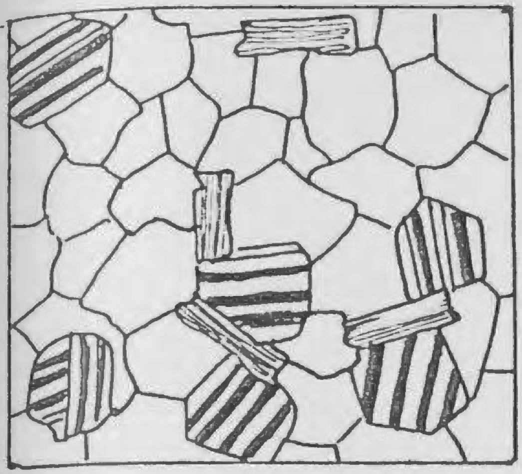
In a few samples of Uivak gneiss which are adjacent to fault zones, some further recrystallization of quartz has taken place in closely spaced linear zones which cut the large, amoeboid grains. These are regarded as fault-related phenomena of purely local extent. The presence of deformation bands and sub-grain structure in many of the large quartz grains does, however, suggest that post-crystallization deformation had some effect on the Uivak gneisses.

The microstructural development of the Uivak gneisses is illustrated schematically in Fig. 7. It is closely comparable to a series of microstructures described by Wilson (1973) from quartzites forming part of a prograde metamorphic sequence in northern Australia.

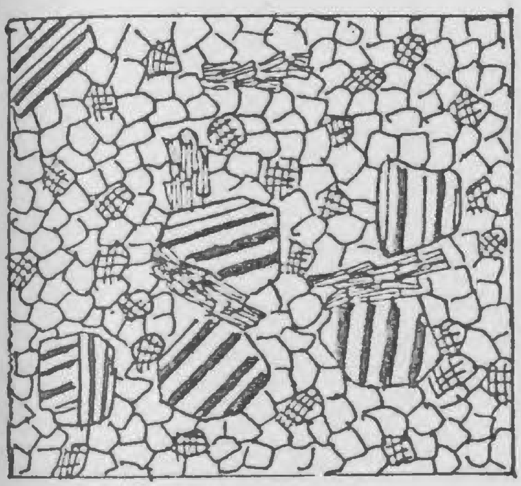
In this example, original detrital quartz grains are replaced completely by aggregates of strain-free polygonal grains under conditions represented by the biotite-cordierite zone in adjacent metasediments. Under conditions corresponding to those of the sillimanite zone, the polygonization is followed by exaggerated growth of a few grains to produce large, amoeboid grains with serrated grain boundaries. In the case of the Uivak gneisses, the nature of the original quartz grains is not known. It is possible that they may have been members of the original igneous assemblages but, in view of the polymetamorphic history of the rocks, it is more likely that they were of metamorphic origin.

The same broad microstructural history can be recognized in the Uivak I gneisses, the pegmatitic leucosome in the Uivak I layered gneisses and in the Uivak II augen

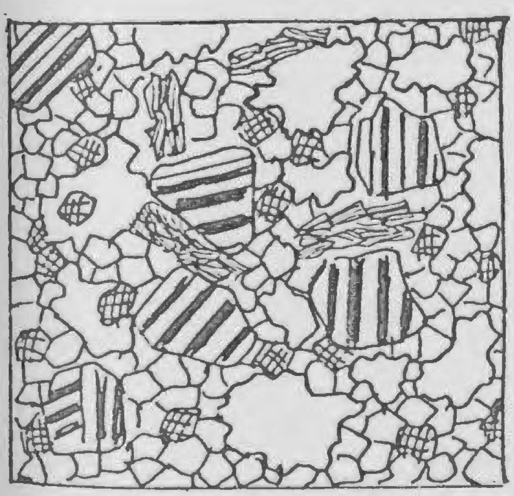
Figure 7 . A schematic diagram illustrating the microstructural development of the Uivak gneisses.



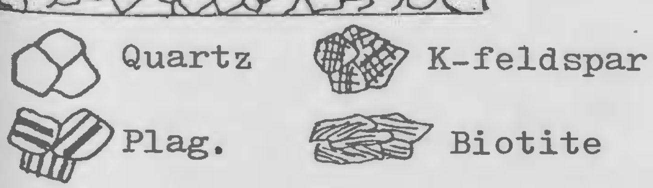
A. Initial coarse grained equigranular granoblastic microstructure . This may have been of igneous or high-grade metamorphic origin .



B. Extensive recrystallisation of quartz to form aggregates of small , polygonal grains . Introduction of fine grained K-feldspar to gneisses . Recrystallisation of large biotite crystals to lepidoblastic aggregates of small flakes . Hornblende and pyroxene-bearing assemblages retro--gressed .



C. Exaggerated growth of a few preferentially oriented quartz grains at the expense of others (secondary recrystallisation). Fine grained polygonal quartz and K-feld--spar preserved in places , resulting in heterogenous , inequigranular micro-structure.



gneisses. Since these three groups of rocks are of demonstrably different ages, it seems reasonable to assume that the microstructures are the results of a metamorphic event which affected all three after the formation of the youngest rocks (the Uivak II gneisses).

Although this event was responsible for extensive recrystallisation in both Uivak I and Uivak II gneisses, it did not cause any significant re-setting of Rb-Sr isotopic systems. Recent work (Collerson, pers. comm.) shows that the Uivak I and Uivak II gneisses define separate Rb/Sr isochrons circa 3,600 Ma and 3,450 Ma respectively, although they have variably responded to events at 2800 Ma, 2500 Ma and 1800 Ma.

The post-Uivak II recrystallization that the microstructural evidence suggests acted upon earlier granulite facies metamorphic assemblages in the Uivak I gneisses, which are partly preserved in places. This earlier granulite facies event may be represented by the 3,600 Ma isochron for the Uivak I gneisses. Early amphibolite facies assemblages would, of course, be very difficult to recognize but may be represented by homogenous tonalitic and trondhjemitic gneisses upon Big Island which are only slightly recrystallized.

The timing of the recrystallization and retrogression of these early assemblages is presently uncertain. Collerson and Bridgwater (1979) suggested that it might have accompanied a massive influx of potassium and rubidium to produce the

3,500 Ma isochron. However, the younger ages (c. 3,450 Ma) recently obtained for the Uivak II gneisses (Collerson, pers. comm.) suggest that any Rb-metasomatism must have taken place before the emplacement of the Uivak II protoliths.

The timing of sagenite development is also very difficult to establish. It is not yet certain whether it formed as a result of hornblende breakdown or whether it reflects sub-solidus exsolution of rutile from titaniferous biotite. If the first mechanism was operative, the development of sagenite accompanied the earlier stages of recrystallization as it is now included in large quartz grains formed by secondary recrystallization. However, if the rutile needles were exsolved from titaniferous biotite, sagenite formation could have taken place at any time and may even be a Hudsonian (c. 1800 Ma) feature. Since sagenitic biotite is also present in the 2,500 Ma old Igukshuak granite suite (Collerson, Kerr and Compston, 1980), this must be regarded as a strong possibility.

The final period of exaggerated grain growth is similarly difficult to place. However, Uivak gneisses in reworked areas show an "annealed" appearance which appears to have resulted from the completion of this secondary recrystallization process. Uivak gneisses outside of these areas show only partial secondary recrystallization. It is perhaps possible, therefore, that the final stages in the evolution of the Uivak gneisses were caused by the events which gave rise to the Kiyuktok gneisses in other areas. The relationship of these events to the earlier polygonization and retrogression is, however, completely unknown.

5.5. THE ORIGIN OF THE KIYUKTOK GNEISSES

Field evidence which supports the hypothesis suggesting that the Kiyuktok gneisses were produced by reactivation of the Uivak gneisses is compelling.

A superb example of a gradational transition between Uivak and Kiyuktok gneisses is preserved in coastal outcrops at Kiyuktok Cove. The transformation of the Uivak gneisses at this locality is a result of two processes. The first of these involved *in situ* transformation which produced heterogeneous rocks characterized by irregular patches of coarse-grained glomeroporphyroblastic Kiyuktok component. At the same time, a second process resulted in the formation and injection of coarse-grained pegmatites containing garnet and orthopyroxene. These pegmatites display clear intrusive contacts with the Uivak gneisses and were obviously at least semi-liquid at the time of emplacement. In terms of field characteristics, the pegmatites are very similar to the patches which formed in place, which suggests that *in situ* transformation may also have involved some kind of melting phenomenon.

The injection of the externally derived material was in most cases associated with static *in situ* transformation of the Uivak gneisses in a border zone adjacent to the pegmatites. The close association of these two mechanisms suggests that they are intimately related and that they operated together. The pegmatites are believed to represent a mobilizate produced by extensive melting of the Uivak gneisses and Upernavik supracrustals at depth.

The common occurrence of partly retrogressed garnet and orthopyroxene in clots within the pegmatites suggests that conditions in the source area were those of the granulite facies.

Outside of those areas where reworking was incomplete and significant quantities of Uivak component are preserved, it is more difficult to prove that the Kiyuktok gneisses were derived by reactivation of the earlier suite. However, many Kiyuktok nebulites contain a "ghost" layering defined by thin zones of fine-grained biotite which is parallel to the compositional layering in surrounding Uivak gneisses. The preservation of this "ghost" layering is interpreted as a result of the greater resistance of the Uivak melanosome to recrystallization and melting.

Where ghost layering is absent, compelling evidence for the derivation of the Kiyuktok gneisses from a Uivak source is present in the form of partly resorbed Saglek dykes.

Recent isotopic work (Collerson, Kerr and Compston, 1980) shows that although Rb-Sr systematics place the Kiyuktok gneisses at circa 2,800 Ma. Whole rock Pb-Pb data suggest an age of 3,505 ± 113 Ma. This age is close to that obtained for the Uivak gneisses and strongly suggests that the Kiyuktok gneisses are derivatives of these rocks.

5.6. MICROSTRUCTURAL FEATURES OF THE KIYUKTOK GNEISSES

In thin section, the Kiyuktok gneisses are a rather enigmatic group of rocks and many of their microstructural features are open to more than one interpretation.

Three types of Kiyuktok component have been distinguished in the previous section. These are: (1) pegmatitic components of intrusive origin, (2) diffuse patches which seem to have formed in place, and (3) nebulitic gneisses whose mode of development is uncertain. A fourth category may be represented by the Uivak component in reworked rocks, which often bears more resemblance to the Kiyuktok component than to unreworked Uivak gneisses.

The purpose of this section is to discuss the features of the Kiyuktok gneisses and the relationships between the different types of Kiyuktok component.

(i) INTRUSIVE KIYUKTOK COMPONENTS:

The simplest of the Kiyuktok components are undoubtedly those which are clearly of intrusive origin. These are homogeneous rocks which, although displaying some evidence of recrystallization, are fairly obvious derivatives of intrusive pegmatites. Compositionally, they are broadly "granitic" and contain large quantities of K-feldspar.

In most cases they contain strained plagioclase of typical "Uivak" appearance and composition (An_{18}-An_{25}) but they also contain some well-twinned albitic plagioclase which often forms a thin rim around strained oligoclase.

The normal mafic phase in intrusive Kiyuktok components seems to be garnet, which is partly retrogressed to green biotite. Schneider (1975) conducted experimental studies of garnet-biotite aggregates of similar morphology in gneisses from the Black Forest. The retrogression of garnet was found to be greatly facilitated by the presence of a silicate melt in the rocks. The reaction relating garnet and biotite can be described simplistically as:

$$\text{Garnet} + K^{+} + H_2O \rightleftharpoons \text{Biotite} + \text{Magnetite} + \text{Si, Al, Ca}$$

where K^+ and H_2O are provided by a hydrous melt which also acts as a transport medium to remove Si, Al and Ca away from reaction sites. The latter elements are incorporated into other silicate phases, which may be represented by the fine-grained epidote which is associated with the biotite.

Some of the intrusive components contain aggregates of fibrous orthoamphibole which is believed to have been produced from orthopyroxene. The amphibole is itself altered to biotite. Although the retrogression of orthopyroxene to amphibole and eventually to biotite has not been studied experimentally, it certainly requires the presence of H_2O and K^+, which could be provided by a hydrous silicate melt.

The field relations and petrology of these Kiyuktok components suggests that they were emplaced as at least partially liquid magmas which contained garnet and orthopyroxene as primary phases. The origin of these two minerals is debatable; they may represent relict xenocrysts but it is possible that garnet crystallized from the magma. Garnetiferous granites are fairly common in the geological record and are interpreted as melts of crustal material and particularly pelitic sediments (e.g. White and Chappel, 1977; Green, 1976). Plagioclase may also have been a relict phase in some examples, since it has a highly strained appearance suggestive of metamorphic origin.

(ii) NEBULITIC KIYUKTOK GNEISSES:

The nebulitic rocks whose mode of development is uncertain are similar in many respects to the Kiyuktok components whose intrusive (and hence semi-liquid) origin is beyond doubt. They contain garnet and orthopyroxene as relict phases and are microstructurally homogeneous. In places they display intrusive contacts with Upernavik supracrustal lithologies and net-vein Saglek dyke inclusions, which indicates that they were at least locally mobile. It is suggested that the Kiyuktok nebulites represent rocks which were in advanced stages of melting. These correspond to the "diatexites" of Mehnert (1968) and Busch _et al_. (1974).

(iii) IN SITU KIYUKTOK COMPONENTS:

In contrast to the above rock types, the Kiyuktok components which clearly formed in situ are heterogeneous rocks which bear more affinity to their Uivak precursors than to Kiyuktok components of intrusive origin.

Their heterogeneous appearance is caused by numerous fine-grained domains which consist of quartz, microcline and albitic plagioclase. Larger quartz and plagioclase grains are comparable in most respects to their counterparts in the Uivak gneisses.

There are two possible explanations for the fine-grained patches in these Kiyuktok components. It is possible that they result from recrystallization of quartz, plagioclase and microcline in the solid state in response to thermal events. This would certainly account for fine-grained quartz and perhaps microcline, but it is difficult to account for the presence of fine-grained albitic plagioclase in this fashion. Since plagioclase was obviously immune to solid-state recrystallization during the evolution of the Uivak gneisses (4.2.4.), why should it be susceptible during the formation of the Kiyuktok gneisses? It is also difficult to explain the regular distribution of the fine-grained domains by a recrystallization mechanism.

The second possibility is that the fine-grained areas represent zones of melt formation. Experimental studies (Mehnert et al., 1973; Busch et al., 1974) show that initial melting in gneisses takes place first at interfaces between quartz, K-feldspar and plagioclase and is thus initiated simultaneously at many different loci. As melting continues, these loci of melting expand and coalesce. In such experimental studies, the melt is easily recognized because it is quenched and hence of "glassy" appearance. In natural rocks, however, rapid cooling would be unlikely and a melt would crystallize as a polycrystalline aggregate of quartz, K-feldspar and plagioclase. The grain size of the resultant aggregate would depend upon rates of cooling and volatile content.

Interpretation of these fine-grained domains as areas of melt formation is also supported by the presence of albite, which would be an essential constituent of any melt form at or near the eutectic minimum in the system Qz-Or-Ab-An-H_2O (e.g. Tuttle and Bowen, 1958; Winkler et al., 1975; Wyllie, 1977).

The "graphic" biotite-quartz intergrowths are also open to two interpretations. The first possibility is that they represent the digestion of biotite by a SiO_2-rich melt. However, experimental evidence (Busch et al., 1974) suggests that biotite melts incongruently to produce a melt and a residue characterized by orthopyroxene, or actinolitic hornblende or an orthoamphibole (anthophyllite). These minerals absorb the Fe and Mg in the biotite structure, whilst potassium (in the form of K-feldspar) and water are incorporated into the developing melt. The reaction for biotite breakdown to orthopyroxene is as follows:

Biotite + quartz $\rightleftharpoons$ Orthopyroxene + K-feldspar + H_2O (Turner, 1968).

Reactions for the formation of amphibole are more complex and release smaller quantities of water, but have essentially the same form.

The spatial relationships between graphic biotite-quartz intergrowths and scattered orthoamphibole or orthopyroxene observed in in situ Kiyuktok components and nebulitic rocks suggests that the graphic intergrowths formed by a reversal of the above reaction.

In the case of the in situ components which are enclosed by Uivak gneisses, the orthopyroxene and/or orthoamphibole which gave rise to the graphic intergrowths must have developed from the Uivak gneisses since it cannot be derived from elsewhere. The obvious mechanism for the development of these minerals is by incongruent melting of biotite via the above reaction.

If this is so, the first stage in the development of the Kiyuktok component was characterized by incongruent melting of biotite to give orthopyroxenes, amphiboles and release water. Later retrogression of the anhydrous phases produced a second generation of biotite which is concentrated into clots where it is intergrown with quartz in a graphic fashion. The second (retrogressive) phase was presumably a result of changing physical and chemical conditions.

This hypothesis is particularly attractive since it explains the localization of biotite into clots within the Kiyuktok gneisses and also the nature of the contacts between the Uivak and Kiyuktok components.

In reworked areas, the Uivak component displays the initial stages of melt formation in the form of small patches of fine-grained quartz, microcline and plagioclase. However, biotite is still distributed regularly throughout the rock, retains a typically intense Uivak pleochroism and only rarely displays "graphic" textures. This suggests that it was not involved in melt formation. However, as soon as biotite starts to break down, H_2O is released as a result of its incongruent melting. The introduction of free water to the system would lower the solidus of the gneisses and would hence favour greater degrees of melting without any substantial change in physical conditions.

Contacts between Uivak components and Kiyuktok components are narrow, gradational zones characterized by a rapid increase in the amount of fine-grained "melt" and by the localization of biotite into "clots". These features are easily explained if the contact zones represent areas where biotite breakdown took place, with the water released by this process greatly increasing the melting capacity of the system.

5.7. THE PROGRESSIVE DEVELOPMENT OF THE KIYUKTOK GNEISSES

The microstructural evidence reviewed in the previous section suggests that it is possible to relate the different types of Kiyuktok components (and hence the different types of Kiyuktok gneisses) to different degrees of melting. This is shown schematically in Fig. 8.

The initial stages of melting are represented within the Uivak component by small patches of fine-grained quartz, microcline and albitic plagioclase. Melting was probably initiated at grain boundaries between these phases with the assistance of small quantities of intergranular fluid in a manner similar to that demonstrated by Mehnert et al. (1973) and Busch et al. (1974).

Uivak components which do not show the presence of a fine-grained "melt" often have an "annealed" appearance. This seems to represent a continuation of the secondary recrystallization (exaggerated grain growth) which took place in the latter stages of the microstructural evolution of the Uivak gneisses (see 4.2.4.). If this interpretation is correct, it may indicate that exaggerated grain growth in the Uivak gneisses was a result of the thermal processes which gave rise to the Kiyuktok gneisses. In areas outside the realm of reactivation, this secondary recrystallization was only partial and earlier polygonal textures were variably preserved. In reactivated areas, grain growth was complete and was followed by partial melting at grain interfaces.

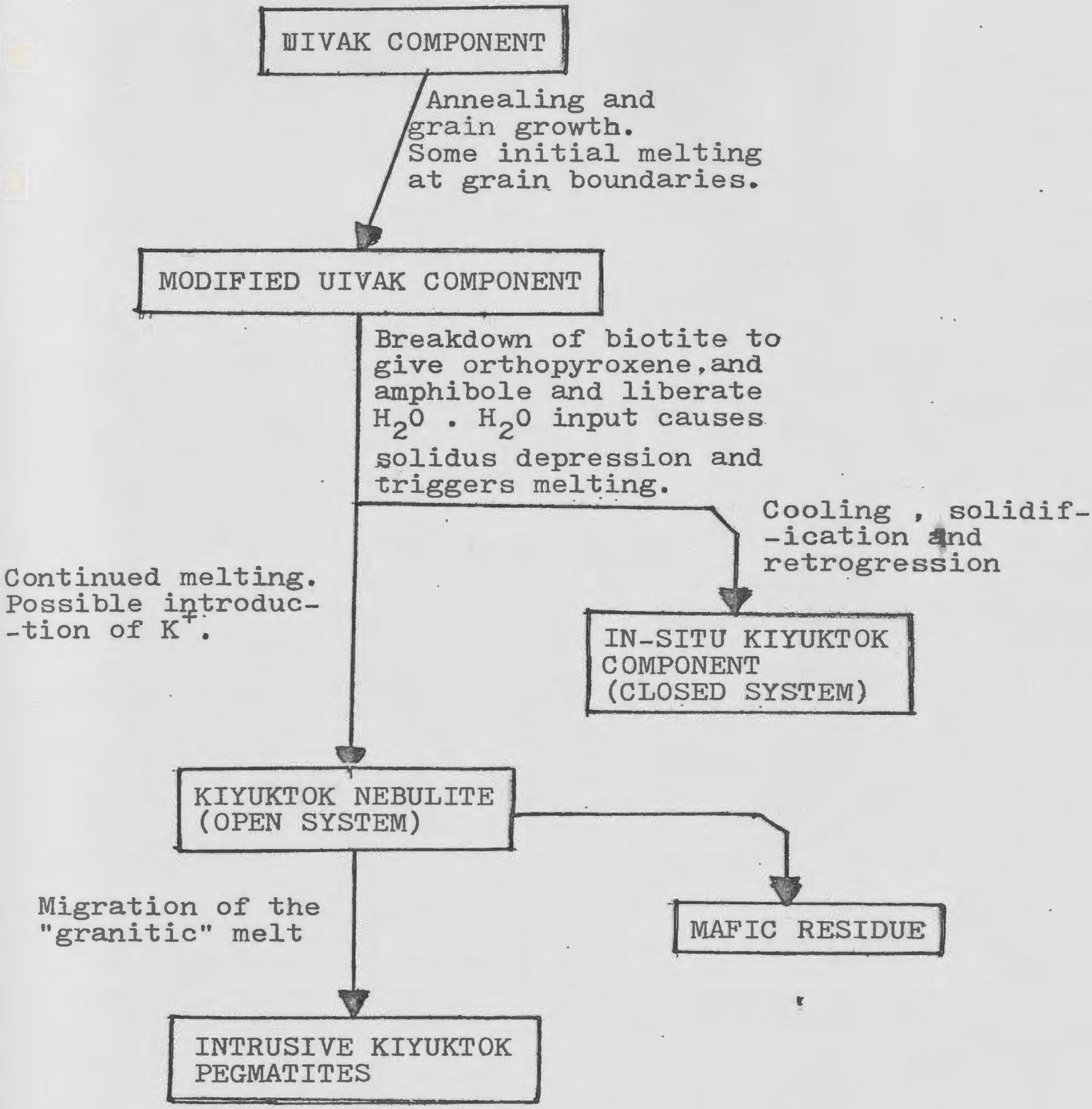


Figure 8 . The Development of the Kiyuktok gneisses in terms of progressive partial melting .

At slightly higher temperatures, biotite became unstable and began to melt incongruently, producing orthopyroxene and amphibole and releasing H_2O and K^+ into the melt. Solidus depression caused by water release resulted in greater degrees of melting. In the case of the in situ Kiyuktok components, this melting was followed by some change in physical conditions (probably a drop in temperature) which caused retrogression of orthopyroxene and amphibole to graphic biotite and crystallization of the silicate melt.

Kiyuktok gneisses which form in this fashion are thus closed systems in which the overall composition of parent Uivak gneiss is retained. Although the localized melt was probably of a composition corresponding to the ternary minimum in the system Qz-Ab-Or-H_2O (e.g. Tuttle and Bowen, 1958; Wyllie, 1977) the overall composition of the rock remains the same because the melt has not migrated.

If, however, there was a further rise in temperature (or a further influx of H_2O from an external source), melting of the gneisses would continue. This stage of advanced melting ("diatexis") is probably represented by the nebulitic rocks which dominate the Kiyuktok gneisses in the study area. These are coarse-grained homogenous rocks which contain fresh, unstrained quartz and microcline. Plagioclase, however, seems mostly to be of relict Uivak origin but displays rims of more albitic composition which may represent products of melt crystallization. Orthopyroxene and/or garnet appear to have been stable mafic phases and are variably retrogressed to biotite, quartz and epidote. In terms of modal composition, the nebulitic gneisses are richer in K-feldspar than the Uivak gneisses or *in situ* Kiyuktok gneisses. This suggests that some externally derived material has been introduced to these rocks.

The Kiyuktok nebulites are at least locally mobile, because they are seen to intrude included Saglek dykes and also locally transgress contacts between quartzofeldspathic gneisses and Upernavik supracrustal rocks. It is thus logical to regard the wholly intrusive Kiyuktok pegmatites seen elsewhere in the complex as mobilizates produced by the separation of the melt from nebulitic rocks at depth. This is consistent with their "granitic" composition and the strained plagioclase and relict garnet and/or orthopyroxene would thus represent samples of the refractory residue.

An evolutionary sequence of the type described above and shown in figure 8 is consistent with field evidence for progressive remobilization of the Uivak gneisses. It is also consistent with the experimental work of Busch *et al.* (1974) which suggests that the incongruent melting of biotite takes place between 700 and 800^{o}C at geologically reasonable pressures (2-8 kb). This is broadly equivalent to temperature estimates derived from mineral assemblages in the supracrustal rocks by a variety of methods (see Chapter 8).

Water seems to have played a crucial role in the development of the Kiyuktok gneisses upon both a local and a regional scale. This is particularly well illustrated by the manner in which *in situ* melting is often localized along the margins of intrusive pegmatites. In view of the small size of the pegmatites, this is unlikely to be a contact metamorphic feature and probably represents the introduction of H_2O from the pegmatites to the country rocks. A sudden influx of water would greatly increase the melting capacity of the system and could trigger *in situ* melting. This type of relationship suggests that the development of the Kiyuktok gneisses was a complex process involving melting and dehydration at different crustal levels within the gneiss complex, and also the transport of material from one level to another. A more detailed discussion of these processes is contained in the final chapter, where a model for the formation of the Kiyuktok gneisses is presented and evaluated in the light of experimental studies.

5.8. GEOCHEMICAL EVIDENCE

A pilot study of the geochemical characteristics of the Kiyuktok and Ikarut gneisses has been carried out as part of this investigation. It was originally intended that trace element and rare-earth element studies would also form part of this report, but, due to problems with equipment, this has not been possible. When these results become available, they will be presented elsewhere.

Representative major element analyses of the Kiyuktok gneisses from the study area are shown in Table 5 (see Appendix).

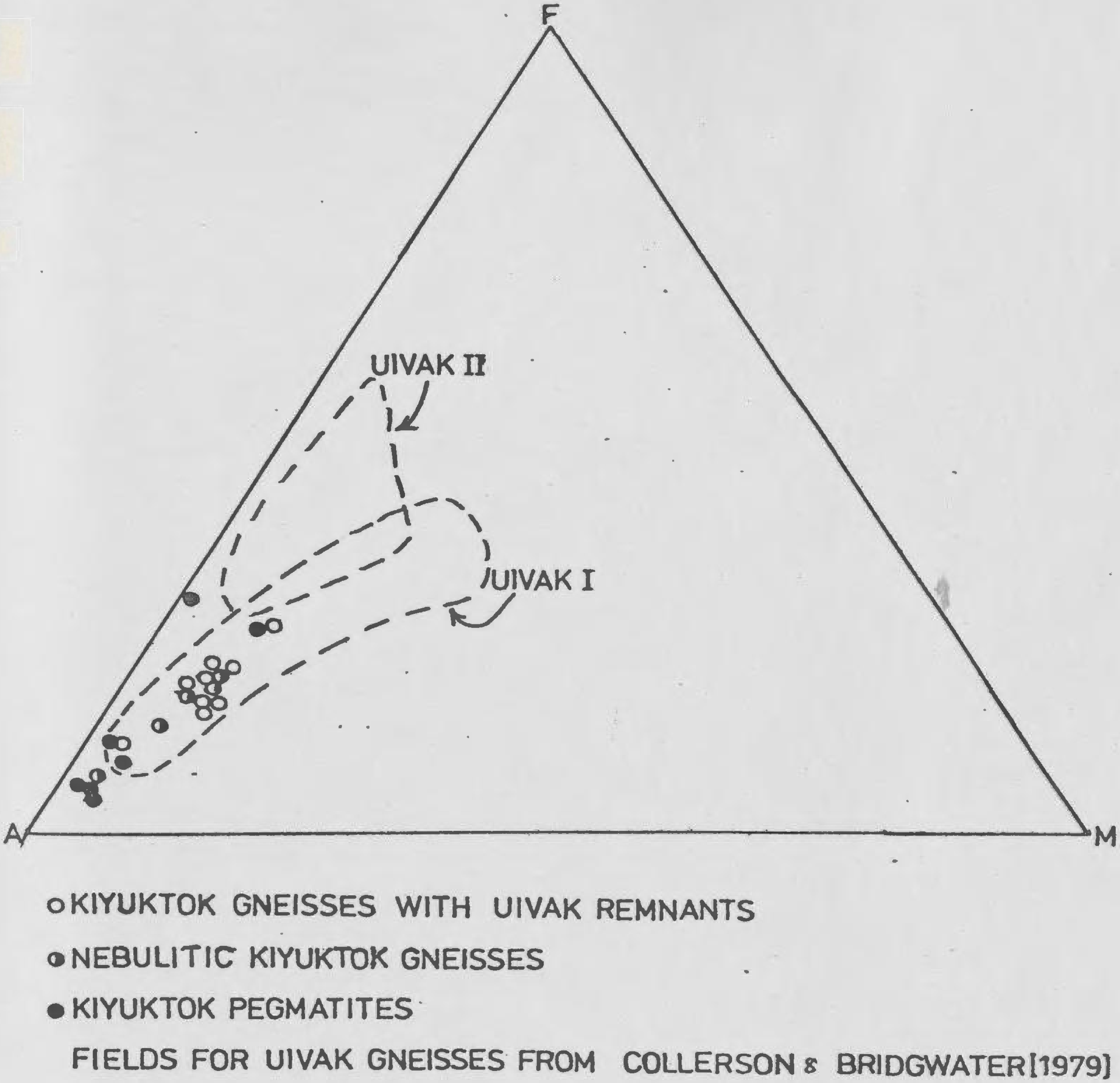
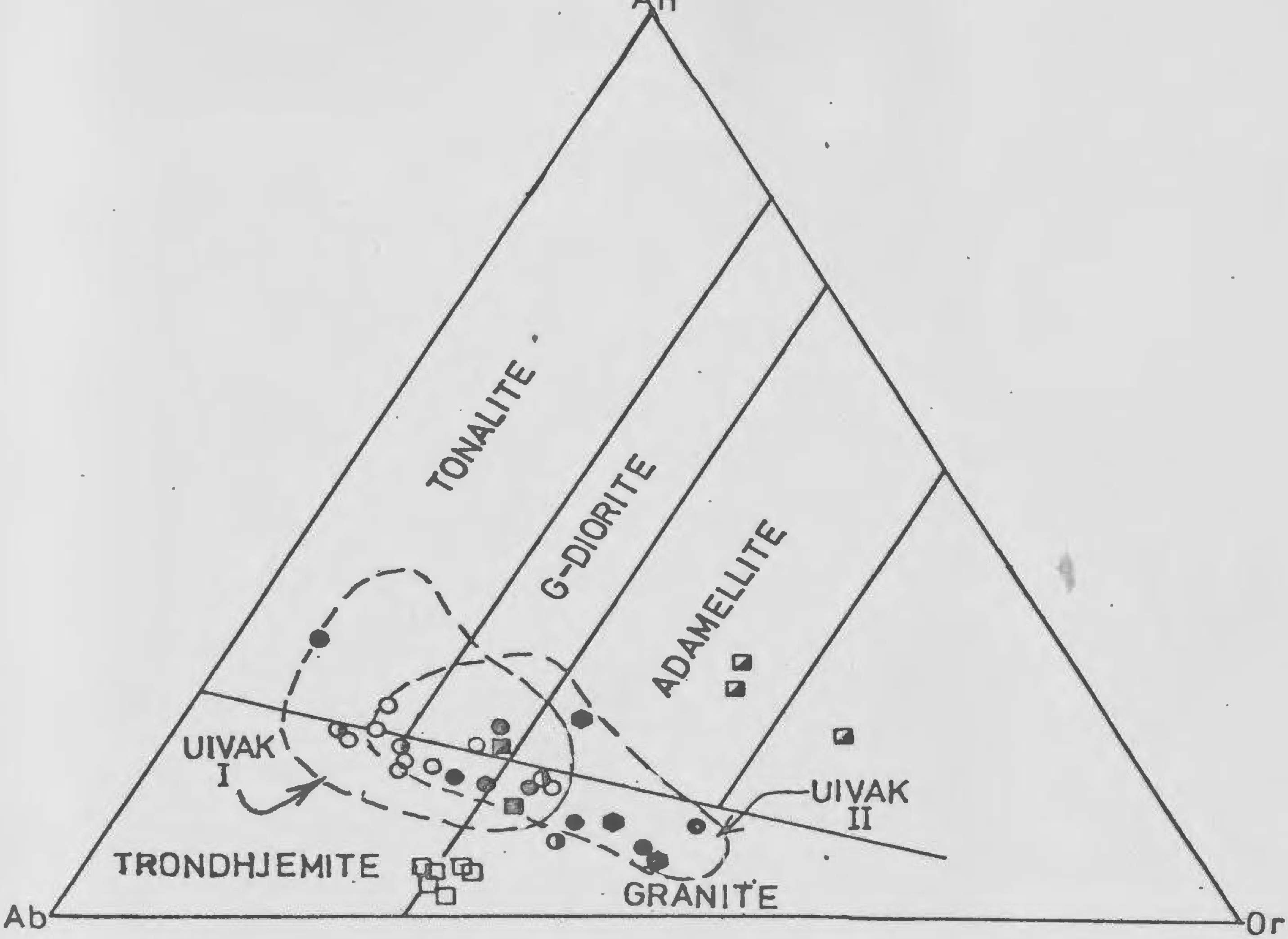


Figure 9 . A-F-M Projection of the Kiyuktok gneisses .



○ KIYUKTOK GNEISSES WITH UIVAK REMNANTS

◐ NEBULITIC KIYUKTOK GNEISSES

● KIYUKTOK PEGMATITES

□ EXP'TAL MELTS OF SIALIC ROCKS [BROWN, FYFE, 1970]

■ " " " " " [BUSCH ET AL., 1974]

◩ " " " PELITES [GREEN, 1976]

⬢ NATURAL GARNET GRANITES [GREEN, 1976]

FIELDS FOR UIVAK GNEISSES FROM COLLERSON AND BRIDGWATER [1979]

CLASSIFICATION OF O'CONNOR [1965]

Figure 10 . Normative An-Ab-Or projection of the Kiyuktok gneisses and various experimental melts .

In terms of major element chemistry, the Uivak and Kiyuktok gneisses are broadly comparable. They plot in the same general areas in both normative An-Ab-Or and AFM projections (Figs. 9 and 10), and show a calc-alkaline trend in the latter. As a group, the Kiyuktok gneisses show higher Na_2O and K_2O contents and larger amounts of normative Or, but considerable overlap between the two is present.

The most interesting results come from the coarse-grained, intrusive pegmatites which form the mobilized portion of the Kiyuktok suite. Most of these garnet and orthopyroxene-bearing rocks are "granitic" in composition and richer in K_2O and Na_2O than other Kiyuktok gneisses and the Uivak gneisses.

In a normative Q-Ab-Or projection (Fig. 11), the Kiyuktok gneisses are also comparable to the Uivak gneisses. Intrusive Kiyuktok pegmatites plot near the centre of the projection (with one exception) and may thus represent minimum melts in this system.

The Kiyuktok gneisses bear some resemblance to minimum melts produced from starting materials with Ab/An ratios of 5.2 - 7.8 (Fig. 11, and Winkler, 1975). However, both the Uivak gneisses and Upernavik metasediments show Ab/An ratios in the range 1:5 - 2:5, where minimum melts would be more Or-rich than typical Kiyuktok pegmatites.

However, these experimental results were derived at pressures of only 2 kb ($P_{H_2O} = P_{LOAD}$) whereas pressures in the study area were probably between 7 and 8 kb (see Chapter 8

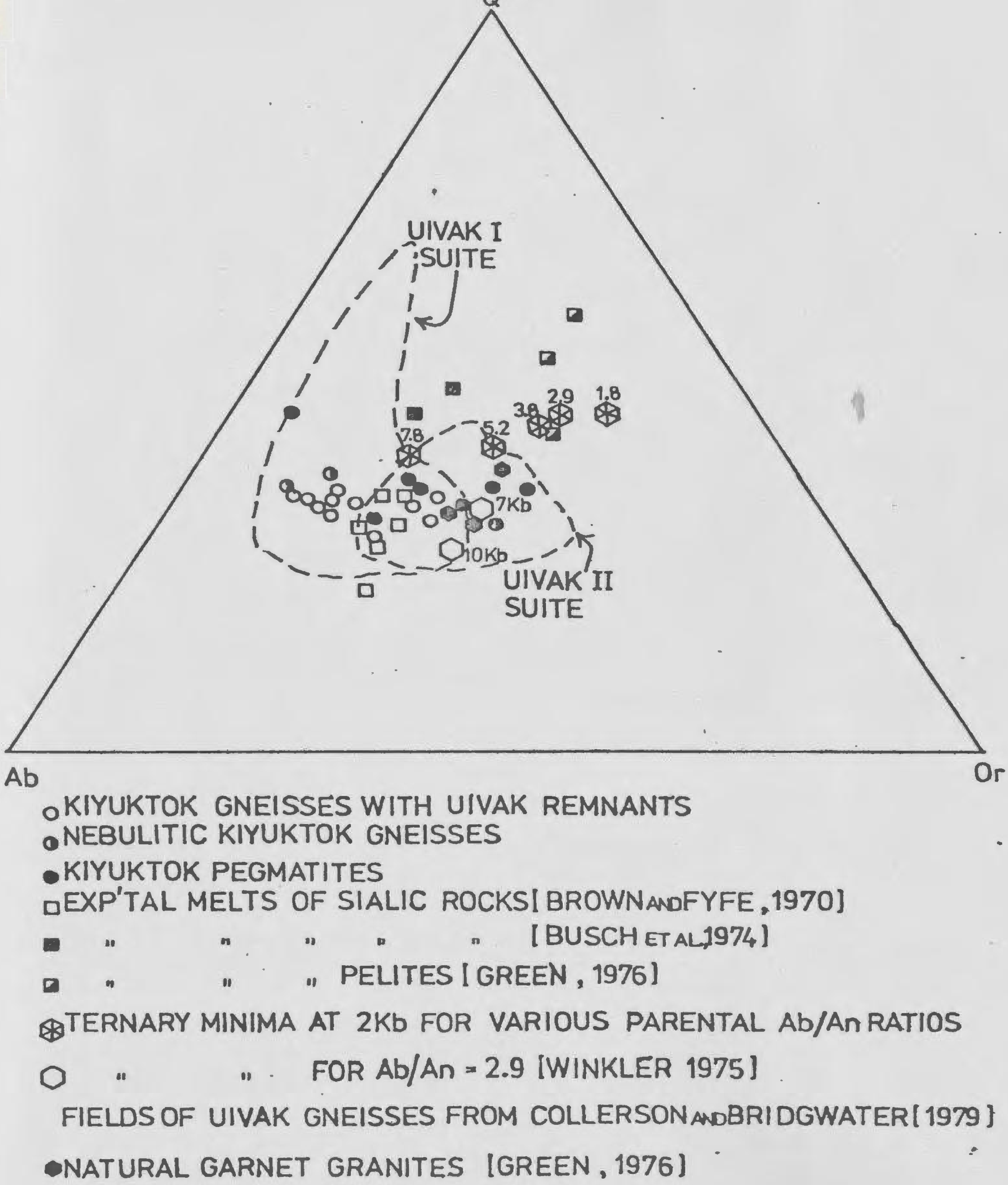


Figure 11 . Normative Q-Ab-Or Projection for the Kiyuktok gneisses and various experimental melts .

for details). Minimum melts for a starting material with Ab/An = 2.9 (Winkler, 1975) at 7 kb and 10 kb are very similar to the Kiyuktok pegmatites.

The Kiyuktok pegmatites are also similar to a number of melts produced from natural starting materials, and in particular, resemble the results of Brown and Fyfe (1970), Busch *et al.* (1974), and Schneider (1975) with dioritic, granodioritic and granitic rocks. The experimental garnet and cordierite-bearing granites produced by Green (1976) from pelitic starting materials are richer in normative Q and Or, but natural garnet-granites are compositionally comparable.

It is unlikely, however, that the Kiyuktok pegmatites represent melts of a single rock type. They were probably produced from both the Uivak gneisses and the Upernavik metasediments and may represent a compositional mixture of the two types of melt. In normative An-An-Or projections (Fig. 10), the pegmatites appear to be intermediate in composition between melts produced from "granitic" and "pelitic" starting materials.

The one pegmatite analysis (KC-78-208A) which displays a "tonalitic" composition may represent a melt produced from mafic starting materials, as it is similar to melts produced by Helz (1976) from basalts at temperatures in excess of 800°C.

The Kiyuktok pegmatites probably do not represent true minimum melts since they may contain variable amounts of "residuum", represented by strained "Uivak"-type plagioclase, and possibly by garnet and orthopyroxene. The more An-rich and Ab-rich nature of Kiyuktok gneisses which are not wholly of intrusive origin is probably explicable in terms of a greater amount of residual "Uivak" plagioclase. This residual material is, in these cases, mixed with a smaller amount of melt of a composition comparable to that of the pegmatites.

Since the melt is still essentially at its point of formation, the overall composition of these gneisses has not changed significantly. Some of the nebulitic rocks, however, show bulk compositions which are similar to intrusive pegmatites, which suggests that significant quantities of melt may have been introduced from elsewhere.

The Ikarut gneisses are compositionally distinct from the other groups of gneisses and are mostly tonalitic and granodioritic. When compared to various experimental melts, they display most similarity to high temperature (800-1000°C) melts of basaltic starting materials (Helz, 1976).

In conclusion, although geochemical evidence cannot prove or disprove the "reworking" hypothesis presented in this thesis, it reinforces arguments presented on the basis of field relations and petrology (Chapters 3 and 4) and isotopic evidence (Collerson et al, 1980).

The overall similarity in composition of most Uivak and Kiyuktok gneisses, and the low-melting point compositions of the Kiyuktok pegmatites, are completely consistent with the evolutionary scheme presented in section 5.7 (see Fig. 8).

CHAPTER 6

SUPRACRUSTAL ROCKS

6.1. INTRODUCTION

The Upernavik supracrustals are dominated by two lithological groups: (1) meta-igneous rocks of broadly "mafic" composition and (2) layered metasedimentary sequences ranging from psammitic gneisses through garnetiferous semi-pelites to rusty pelitic schists. Minor quantities of other metasediments such as quartzites, calc-silicates and iron formations occur in places.

In the context of this thesis, the most important aspect of these rocks is their metamorphic petrology. As far as can be ascertained, equivalent rocks in West Greenland (the Malene Supracrustals) were strongly metamorphosed under amphibolite and granulite facies conditions between 2900 and 2700 Ma ago (Black et al., 1973; Moorbath and Pankhurst, 1976). These dates correspond with those obtained by Rb/Sr methods for the Nuk gneisses of West Greenland and for the Kiyuktok and Ikarut gneisses of Labrador (Collerson, Kerr and Compston, 1980) which are provisionally regarded as equivalents of the Nuk suite.

Although metamorphic ages are not yet available for the Upernavik supracrustals, it seems likely that their mineral assemblages record the effects of the Kiyuktok-Ikarut-Nuk event at this time. The metamorphic petrology of the rocks with sensitive bulk compositions (i.e. mafic and pelitic) are thus of immense importance as indicators of P-T conditions during the events which were responsible for the generation of the Kiyuktok and Ikarut gneisses.

Since the Upernavik supracrustals were in existence well before these events, it is also possible that they may have played a more direct role in the development of these rocks. The potential involvement of the supracrustal suites in the production of younger gneisses will be discussed in a later section.

The petrology described in this chapter (and in the section concerning ultramafic rocks) serves as a framework for a discussion of metamorphic conditions in Chapter 8. Quantitative estimates of pressures and temperatures have been made using geothermometers and geobarometers which utilize the partitioning of elements between co-existing mineral pairs.

6.2. POSSIBLE PRE-UIVAK SUPRACRUSTAL ROCKS

Before proceeding to lithological descriptions of the Upernavik supracrustal rocks, it is advisable to mention the existence of another group of supracrustal rocks which pre-date (rather than post-date) the development of the Uivak gneisses.

These rocks are known as the Nulliak assemblage (Collerson and Bridgwater, 1979) and consist of thinly layered mafic gneisses, iron formations and aluminous meta-sediments which are locally cut by Saglek dykes. Equivalent rocks have been recognized in the Hebron area by Ryan (1977), where they are intruded by homogeneous tonalitic and trondhjemitic rocks regarded as protoliths to the Uivak gneisses.

The Nulliak assemblage is probably equivalent to the Isua supracrustals (e.g. Allaart, 1976) and the Akilia assemblage (McGregor and Mason, 1977) in West Greenland, which pre-date the Amitsoq gneisses.

Within the extensively reworked gneisses which dominate the study area, the recognition of isolated remnants of supracrustal material enclosed in the Uivak gneisses is very difficult. Up until the present time, no unequivocal examples of early supracrustal rocks have been found within the area studied during the preparation of this thesis. Accordingly, the supracrustal rocks described in this chapter are regarded as members of the Upernavik assemblage.

6.3. MAFIC GNEISSES

Gneisses of broadly "mafic" composition are an important constituent of the Upernavik supracrustals and are widespread in the study area. The larger bodies of mafic gneiss (also known as "amphibolites") are easily recognized and delineated in the field due to their prominent positive weathering and conspicuous dark colour. Smaller bodies of mafic gneiss are less easily recognized but are common in all of the quartzofeldspathic gneisses, where they often line up along strike, suggesting that they are fragments of originally more extensive bodies.

6.3.1. Massive Mafic Gneisses

The majority of the mafic gneisses are massive, dense, coarse-grained rocks ranging from grey to dark brown or black in colour. They consist largely of plagioclase and hornblende, but also contain variable amounts of clinopyroxene, orthopyroxene and garnet. The presence or absence of the first two minerals is considered to be largely dependent upon metamorphic grade. Garnet, however, shows a tendency to be restricted to particular layers within the sequence and is thus thought to be at least partly dependent upon protolith composition.

In most of the larger bodies of massive amphibolite, it is possible to recognize a crude, large-scale layering characterized by three principal rock types.

The most abundant is a coarse-grained (3-4 mm) gneiss consisting of plagioclase (15-40%), hornblende $\pm$ clinopyroxene $\pm$ orthopyroxene (50-70% in total; individual proportions variable) and blood-red garnet (0-25%). Where present, garnet occurs as large, subhedral porphyroblasts up to several centimetres in diameter. These are often rimmed by coronal growths consisting of orthopyroxene and plagioclase (Plate 36). These coarse-grained garnetiferous amphibolites and mafic granulites have a distinctive "spotted" appearance in the field.

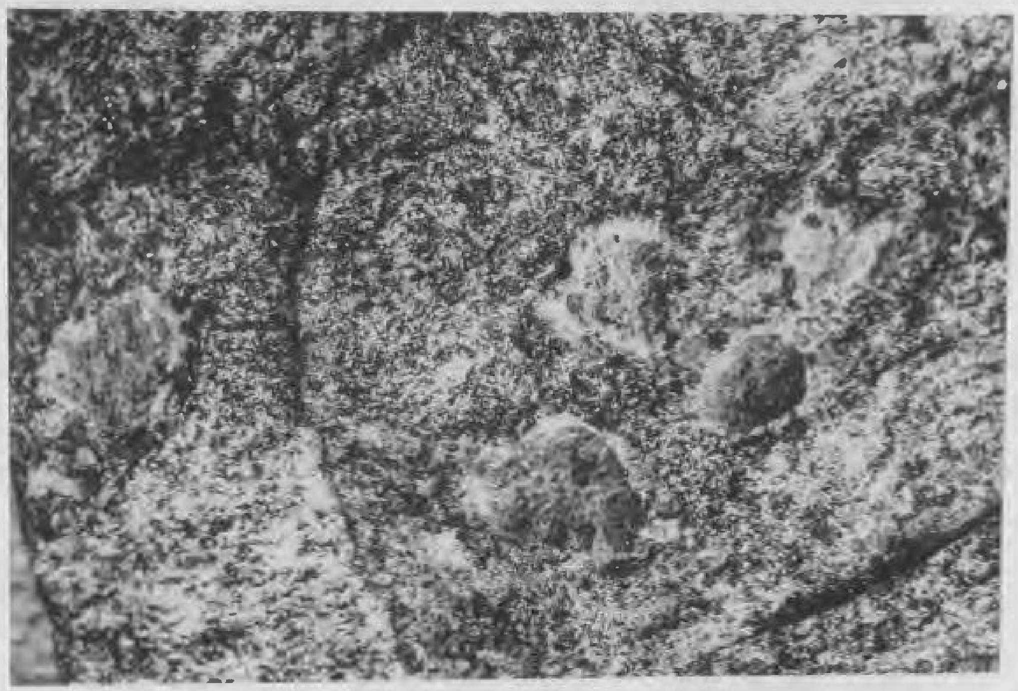


Plate 36 . Garnet porphyroblasts (c.5 cm diameter) rimmed by plagio--clase-orthopyroxene coronal growths . Metagabbroic amphibolite , near Heart Lake .

Plate 37 . Coarse-grained porphyritic meta-leucogabbro forming part of a layered mafic gneiss body . 5 km South of Middle Cove .

Leucocratic mafic gneisses containing between 50 and 70% plagioclase are also important but are volumetrically subordinate to the above rocks. They range from equigranular fine-grained rocks to plagioclase-porphyritic rocks whose textures strongly resemble those of cumulate igneous rocks in areas of low intensity deformation (Plate 37).

Ultramafic rocks (harzburgites, lherzolites, dunites and pyroxenites) form a minor portion of the mafic gneiss belts where they frequently occur along contacts between the mafic gneisses and the Uivak gneisses. Harzburgitic and lherzolitic rocks are the most common lithology and generally contain spinel as the principal aluminous phase. Garnetiferous lherzolites and websterites occur at one locality and contain spectacular coronal structures which record the transformation of garnet to spinel, and eventually to plagioclase. Textures such as these are generally considered to reflect rapid decompression and these rocks have important implications for the origin of ultramafic rocks in the Saglek-Hebron area. They will be described and discussed more fully in the next chapter.

The layering defined by these three rock types is very irregular. Individual layers vary considerably in thickness between 10 and 50 m and cannot normally be traced along strike for more than a few hundred metres. The contacts between the various lithologies are variable in orientation and do not always parallel the regional gneissosity. They are usually sharp, but gradational contacts between the predominant amphibolites and the plagioclase-rich types are seen in places.

A moderate to strong fabric, defined by the alignment of prismatic mafic minerals, is present in all of these rocks. Both planar and linear fabrics are developed, but the former seem most common. The fabrics are most easily distinguished in the leucocratic amphibolites, where they are often isoclinally folded (Plate 38) with the axial planes to these folds lying sub-parallel to the regional gneissosity.

6.3.2. Layered Mafic Gneisses

These are a subordinate group of fine-grained layered rocks of "mafic" composition which bear a clear spatial relationship to the metasedimentary rocks of the Upernavik supracrustals. They are fine to medium-grained rocks of rather nondescript appearance with a millimetre or centimetre scale layering (Plate 39) defined by variations in the plagioclase : mafics ratio and by the presence or absence of garnet crystals. Where garnetiferous, these rocks may contain up to 30-35% garnet, which suggests that they are fairly aluminous in composition. Garnet is sometimes present as porphyroblasts, but is usually of a size range similar to that of the other constituents.

The finely-layered amphibolites sometimes form discrete bodies, but are more commonly interlayered with the

Plate 38 . Isoclinal fold defined by a plagioclase-rich layer forming part of a layered succesion . 2 km South of the West end of Banana Lake

Plate 39 . Finely layered amphibolite considered to be of meta--volcanic origin . West shore of Torr Bay .

metasedimentary rocks and with distinctive bright green calc-silicates containing epidote and diopside. Irregular zones of interlayered metasediments and layered amphibolites are also a common feature of the larger belts of massive mafic gneisses. Contacts between the two groups are frequently discordant.

6.3.3. Petrology

The mafic gneisses display the following mineral assemblages:

(1) Hornblende + plagioclase

(2) Hornblende + plagioclase + clinopyroxene ± garnet

(3) Hornblende + plagioclase + clinopyroxene + orthopyroxene

(4) Hornblende + plagioclase + orthopyroxene ± garnet

(5) Hornblende + plagioclase + orthopyroxene + clinopyroxene + garnet.

The majority of the mafic gneisses are characterized by assemblages (1), (3) and (5). Despite their variation in ferromagnesian constituents, they are all similar in that they almost invariably contain the assemblage Hornblende + plagioclase. Indeed, many of the mafic gneisses in the amphibolite facies areas are effectively bimineralic (assemblage 1) and even those which contain appreciable quantities of clinopyroxene, orthopyroxene and garnet usually contain at least 20-25% Hornblende.

They can thus be regarded as rocks which contain an essential plagioclase-hornblende microstructure which is in some cases modified by the presence of other species.

The plagioclase is typically andesine in the range An_{35}-An_{44} (estimated by optical methods and microprobe analysis). Albite and pericline twinning is well developed and twins often display lenticular or "wedge" shapes suggesting that they developed via deformation, rather than growth. Plagioclase normally occurs as polygonal grains between 0.5 x 0.5 mm and 2 x 2 mm in size, although euhedral megacrysts up to 3 x 2 cm in size are present in leucocratic amphibolites. These megacrysts, however, are usually composed of smaller, polygonal grains.

Hornblende occurs as subhedral prisms and aggregates of a similar size range, but with a noticeable elongation along the c-axis. It is variably pleochroic in shades of yellow, brown and green. In bimineralic hornblende-plagioclase rocks it is typically pleochroic from pale green (X) to yellow green (Y) and deep green (Z). In pyroxene-bearing rocks, however, it takes on a noticeable brown hue, which is a common feature of hornblende in granulite facies rocks (e.g. Binns, 1965).

Hornblende and plagioclase form an equigranular granoblastic mosaic which is typical of all the mafic gneisses (Plate 40). It appears to be a stable, equilibrium assemblage, as grain boundaries are straight and interfacial angles approach 120°.

Plate 40 . Granoblastic hornblende-plagioclase mosaic in a mafic gneiss from Middle Cove .
Crossed nicols . Scale bar 1 mm

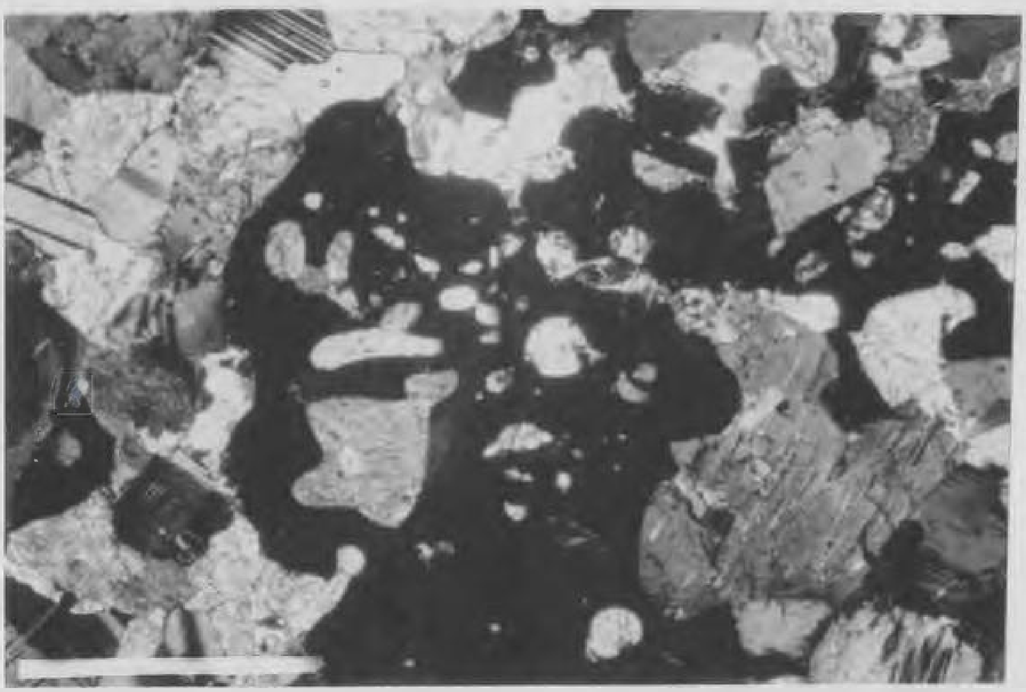


Plate 41 . Poikiloblastic garnet (isotropic) containing inclusions of hornblende , clinopyroxene , orthopyroxene and plagioclase .
Crossed nicols . Scale bar 1 mm .

A colourless to pale green augitic clinopyroxene and a slightly pleochroic (pink to green) hypersthene are important constituents of many mafic gneisses and usually occur together. In most cases they co-exist with appreciable quantities of hornblende, but a few truly anhydrous pyroxene granulites are known to oçcur. Where present, the pyroxenes form an integral part of the granoblastic mosaic. Both orthopyroxene and clinopyroxene appear to be in complete microstructural equilibrium with hornblende, irrespective of the actual proportions of hydrous and anhydrous minerals.

Garnet is commonly present and usually constitutes between 5 and 20% of the rock. In most cases, it too forms part of an equilibrium assemblage with the other constituents, but is sometimes involved in one of two corona-forming reactions. Where it forms part of the equilibrium assemblage, it seems to be a relatively late feature and occurs as large poikiloblasts containing inclusions of all the other mineral species (Plate 41). The garnets often occur in "clusters", which suggests that they are of amoeboid shape and much larger than their two-dimensional expression would suggest.

Garnet is also present in euhedral porphyroblasts with coronas consisting of intergrown orthopyroxene and plagioclase (An_{70-75}) of about 1 mm average grain size (Plate 42). This suggests a reaction of the type:

$$\text{Hornblende + almandine} \rightleftharpoons \text{Orthopyroxene and plagioclase}$$

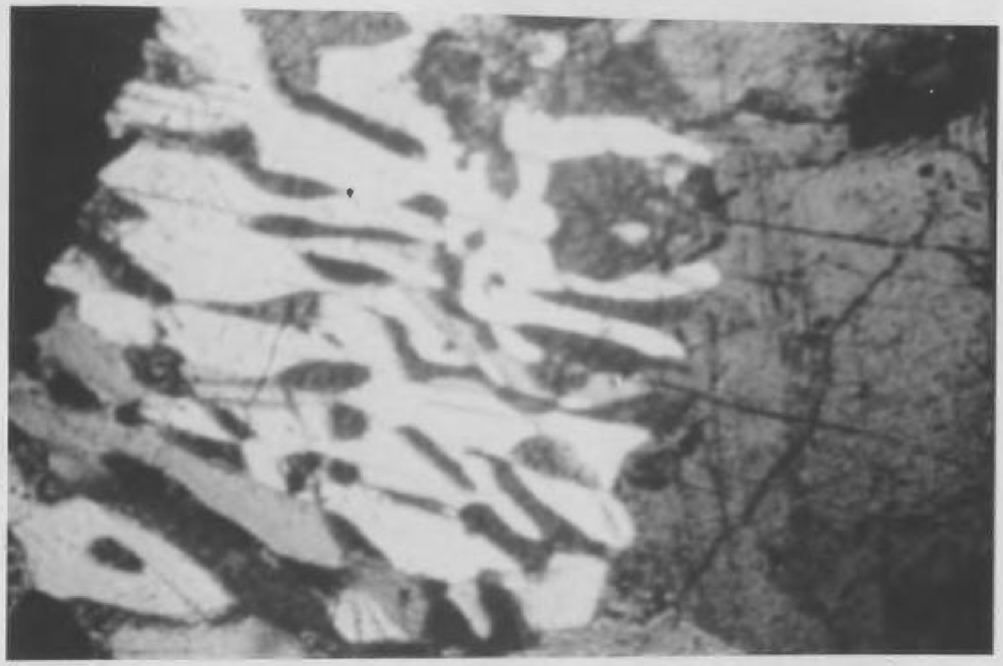


Plate 42 . Orthopyroxene-plagioclase corona developed between garnet (top left) and hornblende(lower right) . This represents the prograde reaction :

$$Gt + Hb + Qz \rightleftharpoons Opx + Pl + H_2O$$

(De Waard , 1965)

Crossed nicols . Scale bar 1 mm .

which is suggested by DeWaard (1965) for analogous coronal structures in Adirondack granulites. In other mafic gneisses from the study area, orthopyroxene and plagioclase often form peculiar graphic intergrowths in the absence of garnet. These are regarded as the end-product of this corona-forming reaction in which garnet has been entirely consumed.

In certain other mafic gneisses dominated by hornblende-plagioclase assemblages, garnet is rimmed and replaced by symplectic intergrowths of hornblende and plagioclase. These are regarded as retrograde coronas formed by the reaction:

$$\text{Garnet} + \text{clinopyroxene} + H_2O \rightleftharpoons \text{Hornblende} + \text{plagioclase} + SiO_2$$

(Carmichael, 1974). Similar structures are described by Misch and Onyeagoche (1976).

The finely-layered amphibolites are similar in most respects to the rocks described above. They tend to be somewhat finer-grained (average grain size less than 0.5 x 0.5 mm) and are much more heterogenous. Layering is frequently visible within single thin sections and is expressed largely by variations in the garnet content of rocks of otherwise uniform mineralogy. The presence or absence of garnet is considered to be largely a function of initial composition.

6.4. METASEDIMENTARY GNEISSES

The metasediments within the Upernavik supracrustals are a varied group of rocks which are dominated volumetrically by pelitic, semi-pelitic and psammitic gneisses. Quartzites, calc-silicates and iron formations form a minor but distinctive part of the assemblage. The metasedimentary gneisses are distinctive in the field because they display a characteristic "rusty" weathering which is caused by disseminated pyrite in the more pelitic members of the assemblage. Unfortunately, this susceptibility to weathering causes some problems in sampling. The rocks are best studied on the coast and are particularly well exposed at Kiyuktok Cove and around Fire Cove. The type area for the supracrustal assemblage is Upernavik Island, which is a direct continuation of the Fire Cove supracrustal belt.

6.4.1. Pelitic and Semi-Pelitic Gneisses

The most common supracrustal lithology is a grey to light brown semi-pelite whose most obvious constituents are quartz, biotite and a lilac-coloured garnet. Blue cordierite, K-feldspar and fibrous sillimanite are prominent in more pelitic types and orthopyroxene and plagioclase are characteristic constituents of the more psammitic examples. They are relatively equigranular rocks with an average grain size of 2-5 mm. In places, however, they are spectacular porphyroblastic gneisses with euhedral garnets up to several centimetres in diameter. A strong foliation is developed in most of these semi-pelites and is defined by biotite alignment and by elongate quartz "ribbons" up to several centimetres long.

Plate 43 . Rhythmically layered pelitic and semi-pelitic gneisses , Upernavik Island .
Photo courtesy of K.D.Collerson .

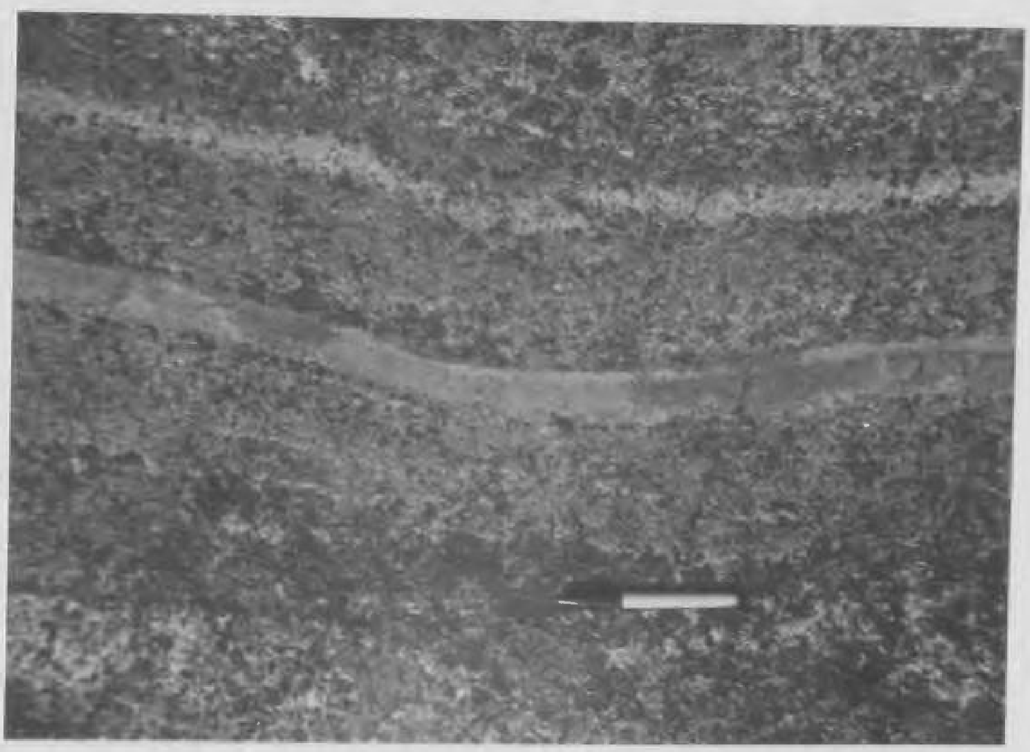


Plate 44 . Thin quartz-rich psammitic layer in semi-pelitic gneisses , Kiyuktok Cove . These layers define rootless intrafolial folds in places .

Interlayered with the semi-pelites are gneisses and schists of pelitic composition (Plate 43) whose mineralogy is dominated by quartz, biotite, K-feldspar and aluminosilicates, with smaller amounts of garnet, plagioclase and cordierite. These pelitic gneisses are often highly migmatised and contain numerous concordant layers of a quartz-microcline pegmatite which in places outline complex intrafolial folds.

The metasedimentary sequences contain disrupted layers and lenses of a more psammitic rock type which is characterized by a quartz-plagioclase-clinopyroxene-orthopyroxene assemblage. These layers often form intrafolial folds whose axial planes are parallel to the dominant layering and foliation in surrounding rocks (Plate 44). The presence of these intrafolial folds suggests that this portion of the layering was derived by the transposition of an earlier layering. The layering within the pelitic to semi-pelitic portion of the sequences is defined in most places by a continuous variation in composition and mineralogy. Thus, rocks of pelitic composition grade continuously into semi-pelites via an increase in the content of quartz, plagioclase and garnet and a concomitant decrease in biotite and sillimanite. The layering so defined often has a strikingly rhythmic appearance, which may perhaps reflect a relict sedimentary layering. However, in other areas contacts between rocks of pelitic and semi-pelitic composition are sharp.

The continuous variation in composition displayed by these metasediments results in a wide range of constituent minerals. In thin section, the semi-pelitic gneisses contain an essential quartz-plagioclase-biotite-garnet assemblage, which is augmented by cordierite, and/or orthopyroxene in some examples. The more biotite-rich semi-pelites contain sillimanite and microcline in small amounts.

The pelitic gneisses and schists are usually biotite-rich rocks containing abundant sillimanite and microcline, with correspondingly smaller amounts of quartz, plagioclase and cordierite. Orthopyroxene is sometimes present.

The semi-pelitic gneisses are dominated by quartz (25-35%), plagioclase (25-40%) and garnet (20-30%). Quartz and plagioclase form an inequigranular mosaic characterized by large, amoeboid grains of quartz and smaller, subhedral plagioclase grains. Plagioclase compositions are highly variable (An_{35}-An_{55}) but are usually consistent within individual samples. Quartz grains are often strongly elongated and form quartz ribbons composed of interlocking amoeboid grains in the more strongly foliated examples.

Garnet is a major constituent of the semi-pelites and often makes up over 50% of the rock by volume. Variations in garnet content (and related variations in biotite content) help to define the compositional layering which is sometimes visible within individual thin sections. Garnet porphyroblasts are euhedral and inclusion-free. They are pre-tectonic with respect to the foliation defined by biotite and other mafic species, which wraps around the porphyroblasts and forms distinctive "augen" textures in strongly-deformed rocks.

Biotite is the most common mafic mineral and is present in highly variable amounts, being most abundant in rocks of more pelitic affinities. It is moderately pleochroic from yellow (X) to orange-red (Y = Z) and is present both as euhedral crystals up to 1 mm long and as lepidoblastic aggregates of small flakes. Alignment of biotite crystals and/or aggregates defines a prominent foliation which is parallel to quartz ribbons and wraps around garnet porphyroblasts.

Rocks which are intermediate in composition between semi-pelites and pelites often contain cordierite, orthopyroxene and sillimanite in addition to the essential assemblage described above.

Cordierite forms part of the mosaic defined by quartz and plagioclase, with which it appears to be in microstructural equilibrium. It is sometimes altered to fine-grained muscovite and chlorite ("pinite"; Schreyer, 1958), but is usually fresh and displays complex polysynthetic sector twinning.

Orthopyroxene, where present, is invariably associated with biotite and assists in defining a prominent foliation. In most cases it appears to be in microstructural equilibrium with biotite, but in a few examples it appears to replace the latter. Small quantities of microcline are sometimes associated with orthopyroxene-biotite aggregates, suggesting a reaction of the form:

$$\text{Biotite + quartz} \rightleftharpoons \text{Orthopyroxene + K-feldspar} + H_2O$$

(Turner, 1969).

The pelitic gneisses and schists are comparable in most respects to the above rocks but tend to be richer in biotite, which may make up as much as 25-30% of the rock. Microcline is also a prominent constituent and usually predominates over plagioclase.

Sillimanite is abundant and, together with biotite, defines a strong foliation which wraps around pre-tectonic garnets (Plate 45). Sillimanite is present in one of two forms; either as fibrous aggregates ("fibrolite") or as euhedral prisms up to 2 mm in length. Orthopyroxene is present in some pelitic gneisses, where it appears to form at the expense of biotite.

6.4.2. Homogeneous Psammitic Gneisses

Within the pelitic and semi-pelitic sequences, rocks of psammitic composition are restricted to thin, discontinuous layers. However, massive homogenous psammites exist in a few areas and form a distinctive group of rocks known informally as the "green gneisses" (Plate 46). These are best exposed along a coastal strip along the west side of Middle Cove where they form a continuous belt which can be traced inland for several kilometres. They appear to form part of the Fire Cove

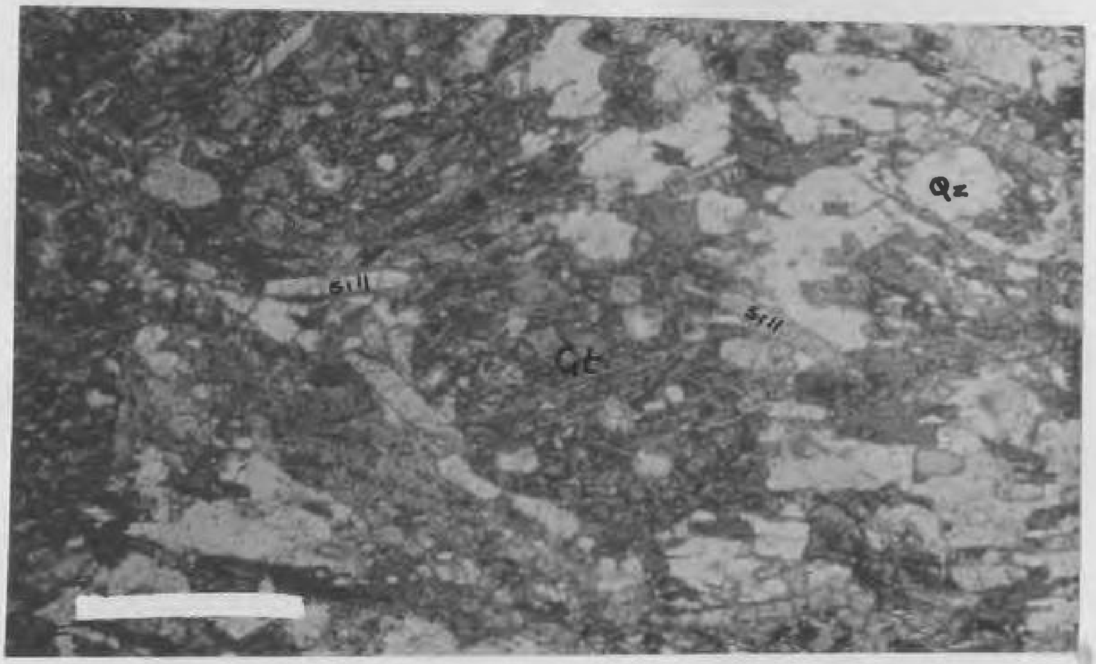


Plate 45 . Pre-tectonic garnets augened by biotite-sillimanite foliation . Pelitic gneiss from Torr Bay . Plane polarised light . Scale bar 1 mm .

Plate 46 . Massive psammitic gneisses (green gneisses) containing thin pegmatite layers . Middle Cove , Western shore .

supracrustal belt in this area. The green gneisses are also exposed in the area around Bob's Pond, where they define an important fold closure. In the field, they appear as equigranular rocks of a dirty grey-green colour which contain lenses of calc-silicate and pelitic to semi-pelitic gneisses.

In thin section, they contain small (<1.0 mm max. dimension) grains of both orthopyroxene and clinopyroxene which, together with a red-brown biotite, define a strong foliation. The mafic minerals form 10-20% of the gneiss. The remainder consists of an equigranular granoblastic elongate mosaic of quartz and plagioclase (An_{30}-An_{35}).

The green gneisses are similar in most respects to the thin layers of psammitic composition in the pelitic to semi-pelitic successions, which display equivalent mineral assemblages.

6.4.3. Quartzites and Other Metasediments

These are a minor but highly distinctive part of the metasedimentary assemblage. They typically occur as thin layers or isolated lenses which are always associated with and often enclosed within more common metasedimentary rocks. Three types are recognized within the study area: (1) Hedenbergite-quartzites, (2) Garnet-quartzites, and (3) Bright green fuschite quartzites.

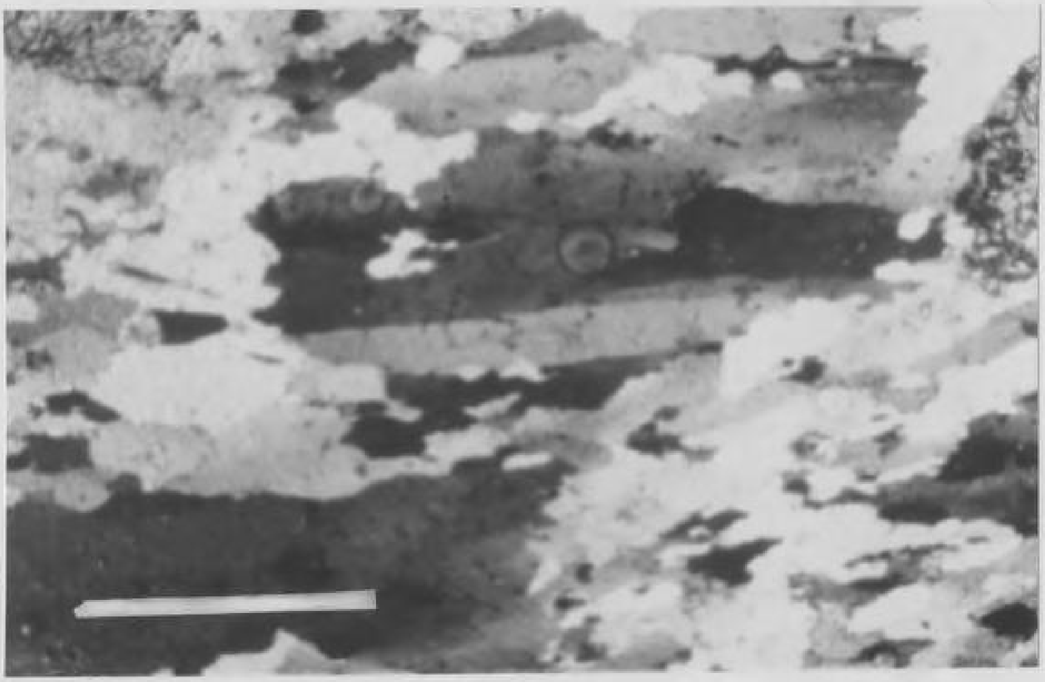


Plate 47 . Elongated amoeboid quartz grains ("ribbon quartz") in a granulite facies quartzite from Torr Bay . Note prominent deformation lamellae lying parallel to foliation and scattered clinopyroxene (high releif) Crossed nicols . Scale bar 1 mm

The pyroxene-bearing quartzites are very spectacular rocks consisting of 80-90% quartz and 10-20% bright green hedenbergite, which is partially replaced by amphibole. The mafic minerals are preferentially concentrated in distinct linear zones throughout the rock. Quartz microstructures are rather spectacular and are dominated by extremely large amoeboid quartz grains (Plate 47) believed to have developed via exaggerated grain growth. These rocks are exactly analogous to upper amphibolite and granulite facies quartzites described from Australia by Wilson (1973) who was able to document the development of this type of microstructure.

Garnetiferous quartzites are rather infrequently associated with pelitic and semi-pelitic gneisses and are similar in most respects to the above rocks. They do, however, contain significant quantities of biotite and sometimes plagioclase, suggesting that they may simply be a very quartz-rich member of the layered sequences, perhaps somewhat akin to the "green gneisses".

Fuschite-bearing quartzites are spectacular and distinctive in the field because of their striking pale green colour. They are often layered rocks, with some layers consisting of almost pure quartz. In thin section they contain over 98% quartz (with microstructures comparable to other quartzites) and small quantities of fine-grained disseminated mica.

Calc-silicates and banded iron formations are found in some parts of the Saglek-Hebron area, but are not particularly abundant in the study area. They have not received any detailed study as part of this investigation.

6.5. THE ORIGIN OF THE SUPRACRUSTAL ROCKS

Whatever their composition, the Upernavik supracrustal rocks invariably display mineral assemblages which are characteristic of either the upper amphibolite facies or the granulite facies. Reaction relationships leading to the production of these assemblages are only rarely preserved and the rocks appear to have equilibrated completely to ambient metamorphic conditions. More precise estimates of these conditions are presented in Chapter 8, where techniques of geothermometry and geobarometry have been applied to coexisting mineral pairs.

By analogy with younger terrains, the psammitic, pelitic and semi-pelitic metasediments are probably derivatives of clastic sandstone, siltstone and shale sequences. The original sedimentary layering is preserved in the compositional layering, although it has been extensively transposed in most parts of the complex. The distribution of rock types suggests that there might originally have been two "facies", one of which was dominated by psammitic rocks (now represented by the "green gneisses") and the other by the more abundant pelites and semi-pelites, which contain minor psammitic rocks.

The quartzites in the metasedimentary sequences could either be derivatives of especially pure quartz sands (as suggested by Nieuwland, 1979) or possibly of impure cherts. Hedenbergite quartzites are commonly associated with quartz-ironstones, which suggests that they might have been some form of related chemical sediment.

Field evidence suggests that there are two groups of mafic gneisses. The finely-layered amphibolites which are associated with the metasediments are regarded as derivatives of volcanogenic sediments (tuffs and agglomerates) or lava flows. The layering is regarded as a result of the attenuation of original inhomogeneities such as breccia and agglomerate structures and altered pillow margins caused by seawater-lava interaction. In the case of meta-tuffaceous rocks, some sedimentary layering may have been originally present. Original volcanic textures have not been reported from Labrador, but are reported from West Greenland by Myers (1976b, 1978), where they can be traced into analogous layered amphibolites of the Malene succession.

The massive amphibolites are regarded as meta-intrusive rocks which were originally intrusive into the volcano-sedimentary successions described above. An intrusive origin is strongly suggested by their relatively homogeneous appearance and by the preservation of euhedral plagioclase megacrysts and cumulate textures in some of the more leucocratic varieties. Discordant contacts between massive amphibolites and metasedimentary rocks are fairly common and good intrusive relationships are preserved on Shuldham Island.

The ultramafic rocks which are associated with the meta-intrusive amphibolites were possibly once part of a cumulate succession, similar to that reported from the Hebron area by Ryan (1977). It is also possible, however, that the ultramafic rocks are allochthonous rocks marking zones of thrusting developed during the intercalation of the Upernavik supracrustals and the Uivak gneisses. This hypothesis is supported by the occurrence of ultramafic rocks along contacts between metasediments and Uivak gneisses. This problem will be discussed further in later chapters.

The Upernavik supracrustals (and the equivalent Malene supracrustals of West Greenland) are traditionally regarded as younger than the Uivak or Amitsoq gneisses. This supposition is based largely upon the absence of Saglek or Ameralik dykes in the supracrustal lithologies. However, as McGregor (1973) points out, this difference may not be significant since the two groups of rocks may have originated in different areas and juxtaposed by later thrusting. Glikson (1977) suggests that the Upernavik supracrustals are older than the Uivak gneisses on the basis of an analogy with greenstone-belt successions where early sediments and volcanics pre-date tonalites and trondhjemites. However, in view of the lack of understanding concerning relationships between high-grade and low-grade Archean terrains, the value of such an analogy is doubtful.

A much more interesting possibility is suggested by Chadwick and Coe (1976) who propose that the Ameralik dykes represent feeders to layered basic successions in the Malene assemblage and are thus of equivalent age. If this is so, the lack of Saglek dykes in the Upernavik supracrustals is easily explained, and the striking similarity between porphyritic Saglek dykes and the leucocratic portions of the amphibolite bodies is much easier to understand. This does not, however, change the essential hypothesis that the supracrustal rocks post-date the Uivak gneisses if the two groups originated in the same area.

Some of the above arguments are also treated by Bridgwater and Collerson (1977) in a reply to the criticisms of Glikson (1977).

CHAPTER 7

ULTRAMAFIC ROCKS

7.1. FIELD RELATIONS

Rocks of ultramafic composition (dunites, peridotites and pyroxenites) are a volumetrically unimportant group of rocks but are widespread throughout the Archean Complex.

They are normally restricted in areal extent and most commonly occur as pods or lenses which rarely exceed 100 m in length. These small bodies are frequently found in "trains" within the surrounding gneisses, which can be traced along strike for distances up to 1 km in places. These boudin trains are regarded as fragments of originally more extensive bodies, These may be represented by a few isolated ultramafic units of greater size which range up to 1 km strike length and 2-300 m thickness.

The ultramafic rocks are present in a number of settings. Many of them are associated with the massive mafic gneisses of the Upernavik supracrustal suite and characteristically occur along contacts between these rocks and the Uivak gneisses. It is debatable whether this association reflects a genetic relationship between the ultramafic rocks and the amphibolites. Although compositional layering is present in both groups of rocks, gradational contacts between the two have not been recognized in the Saglek area. However, Ryan (1977) and Martin (1978) have described gradational contacts between coarse-grained pyroxenites and metagabbros in the Hebron area, suggesting that the two groups of rocks were cogenetic.

Ultramafic pods and lenses are also associated with metasedimentary gneisses,with which a genetic connection is more difficult to envisage, and in places are completely enclosed by Uivak or Kiyuktok gneisses.

Whilst it remains possible that some of the ultramafic rocks once formed parts of layered intrusions with Massive Upernavik amphibolites, the above evidence would suggest that most of them are not related to any particular rock type. It is perhaps more likely that the ultramafic rocks are a completely separate group of rocks which were intercalated with the other members of the complex by thrusting. This suggestion is supported by the occasional preservation of high-pressure mineral assemblages characterized by garnet and will be further discussed at the end of this chapter.

In the field, the ultramafic rocks are easily distinguished by their prominent red weathering and positive relief. Their contacts with other rock types are almost invariably sharp and are interpreted as tectonic. Where a strong fabric is present in the surrounding gneisses, it wraps around the contacts and is weakly developed in the outer parts of the body. The interior portions of the ultramafic units, however, are usually massive, fresh and unaltered (Plate 48).

Plate 48 . A dunite body with a schistose margin and a massive , undeformed interior . Middle Cove .

Plate 49 . Metasomatic biotite rim around an ultramafic block enclosed by granitic material in the agmatite zone at Torr Bay . Block is approximately 1 m across .

The rocks themselves are compositionally varied and range from diorites to harzburgites and lherzolites, with subordinate pyroxenites and hornblendites. They are variably altered and serpentinized, with the majority of the alteration being confined to smaller bodies or to the margins of larger units. The mineral assemblages in these rocks are, for the most part, of metamorphic origin, although most of them are believed to have developed via isochemical recrystallization of equivalent igneous assemblages. In a few instances, though, ultramafic rocks appear to retain a partially recrystallized igneous assemblage.

Metasomatic alteration is important in areas where ultramafic rocks come into contact with late pegmatitic and granitic rocks, such as within the agmatites at Torrbay. In these instances, metasomatism results in the formation of a monomineralic biotite zone around the margins of the ultramafic unit (Plate 49).

In the descriptions of lithology and petrology contained in the following sections, most attention is paid to the "primary" assemblages which reflect either original igneous mineralogy or the effects of high-grade metamorphism. Later alteration and serpentinization are unimportant from the point of view of this thesis and are not considered; only the fresher rocks are described.

7.2. HARZBURGITES AND LHERZOLITES

The majority of the ultramafic rocks in the study area display mineral assemblages dominated by olivine and orthopyroxene which, by analogy with equivalent igneous rocks, are best termed harzburgites. A subordinate group of rocks contain olivine, orthopyroxene and clinopyroxene and appear to be analogous to lherzolites. In the field these are massive, homogeneous rocks which display a green-brown weathering but are black or bluish in colour where fresh. They are normally coarse grained and equigranular, with average grain sizes falling between 1 and 4 mm.

In thin section, forsteritic olivine and a pleochroic (strongly red to green) orthopyroxene are the most obvious constituents. These are usually present in equal or sub-equal amounts and accompanied by variable quantities (10-45%) of a pale green pleochroic amphibole. These three minerals collectively form an equigranular granoblastic mosaic displaying stable 120^{o} interfacial angles. In some of the more strongly foliated examples, large elongate grains of olivine are seen lying parallel to the dominant foliation (Plate 50). Deformation bands within these grains either lie parallel to this foliation or intersect it at low angles. These large, strained olivine grains may represent original igneous crystals which have been partially recrystallized during metamorphism.

A macroscopic layering defined by variations in the ratio of olivine to orthopyroxene is visible in many harzburgite

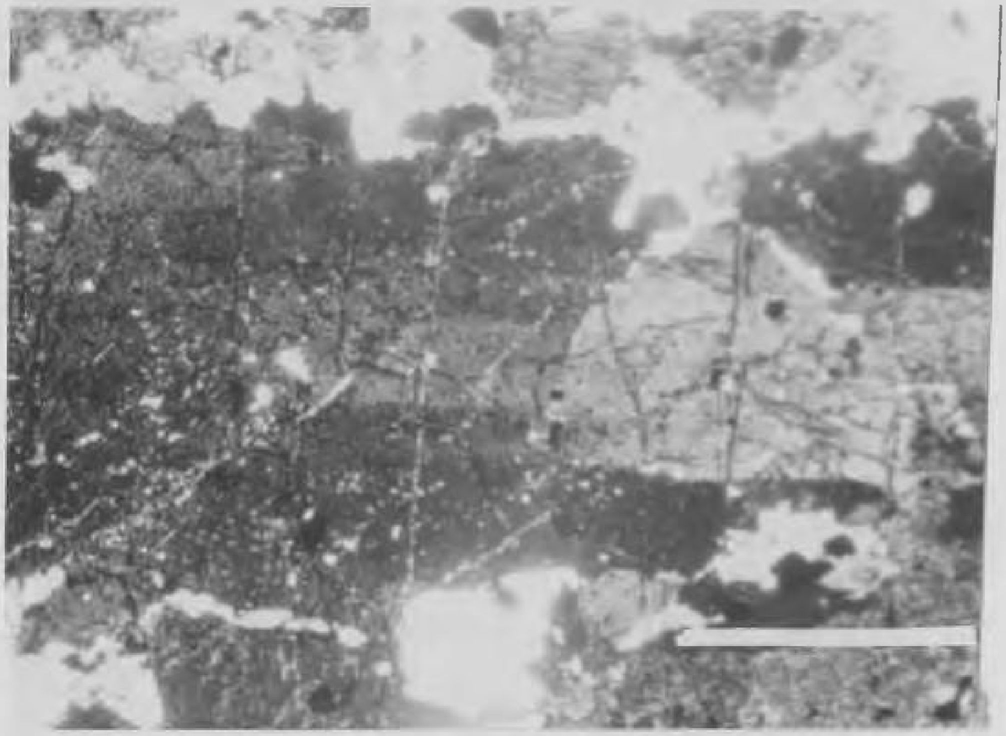


Plate 50 . A large (igneous?) olivine grain displaying prominent deformation lamellae parallel to the foliation . Crossed nicols . Scale bar 1 mm

Plate 51 . Pseudo-spinifex texture formed by prismatic metamorphic olivines in a dunite . 3 km East of Kiyuktok Cove .

outcrops and is sometimes present within a single thin section. The proportion of pale green amphibole in the rocks appears to remain constant throughout.

Olivine green hercynitic spinel is the most prominent minor constituent and characteristically occurs as small anhedral grains (0.1-0.2 mm) which are interstitial to olivine, orthopyroxene and amphibole. A similar growth habit is displayed by small iron oxide grains and by chromite.

Pale brown phlogopitic mica is prominent in some examples and appears to be in complete microstructural equilibrium with the other constituents and does not obviously replace any other mineral. In places it defines a foliation which is also expressed by amphibole alignment and (sometimes) by the elongation of olivine grains.

Lherzolitic rocks are less abundant than harzburgites but are similar in most respects. In addition to the constituents listed above, they contain variable quantities of a pale green augitic clinopyroxene which forms part of the granoblastic mosaic with olivine and orthopyroxene. Lherzolites occur in places as members of layered sequences with harzburgitic rocks, but are also present in discrete, small bodies which are not associated with other ultramafic lithologies.

7.3. DUNITES

Rocks composed of more than 95% olivine form a minor part of the ultramafic suite and are normally associated with harzburgitic rocks, although they occur alone in a few areas. One particularly large dunite body occurs along the western side of Bracelet Lake, where it is associated with Upernavik amphibolites, and a smaller unit occurs within quartzofeldspathic gneisses at Middle Cove. Outside of these two areas, dunites are restricted to small pods and lenses associated with other ultramafic rocks.

In the field, they are green or red-weathering rocks which display either a granular texture or, more rarely, a pseudo-spinifex texture (Plate 51) defined by large, prismatic metamorphic olivines. Similar textures are reported by Collerson et al. (1976b) from the Hunt River belt and other parts of the Saglek area. The prismatic olivines appear to post-date the development of a planar fabric in the rocks, and are thus probably of metamorphic, rather than igneous origin.

In thin section, dunites display an equigranular granoblastic mosaic suggesting a high degree of microstructural equilibration (Plate 52). Small amounts of colourless orthopyroxene and opaques are present as accessory minerals. Occasional thin (1-10 cm) layers of orthopyroxenite occur within them and have a consistent orientation within individual outcrops. The origin of these pyroxenite layers is problematical; they may represent cumulate layers, but might also represent intrusive veinlets which have a consistent orientation.

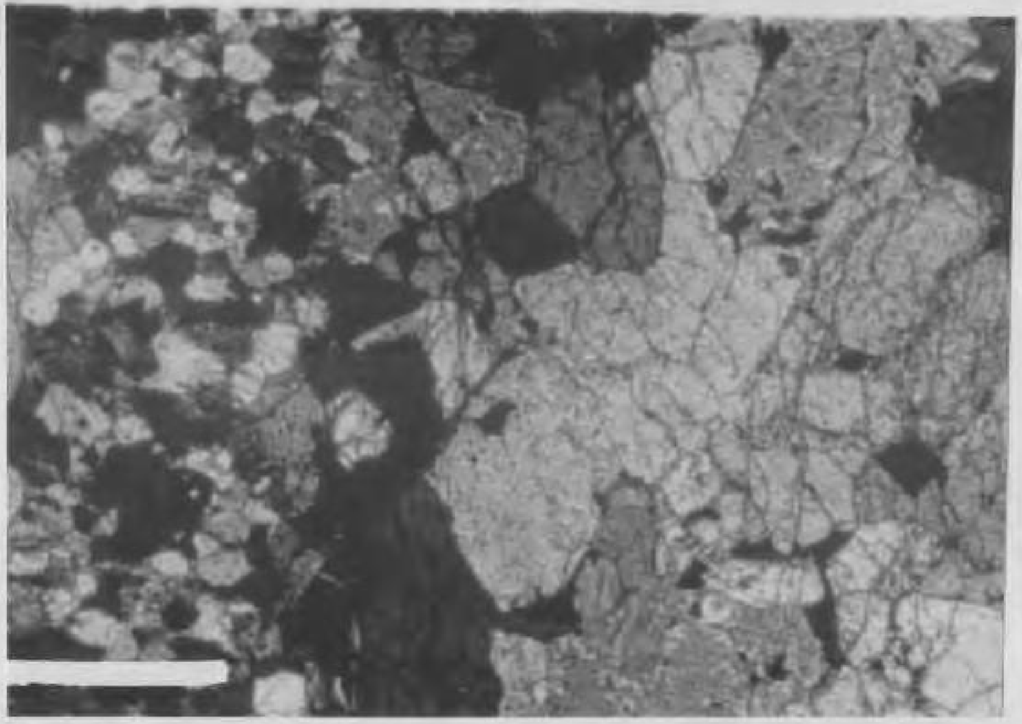


Plate 52 . Granoblastic mosaic of olivine grains in a dunite .
Fine-grained orthopyroxenite layer (possibly of cumulate origin) at left .
Crossed nicols . Scale bar 1 mm .

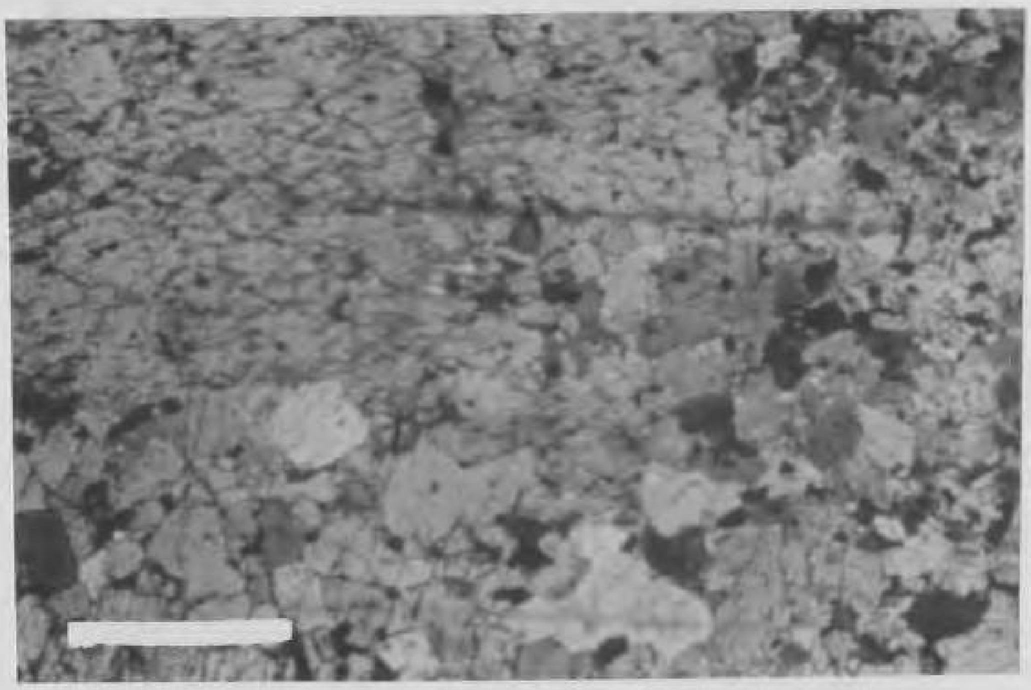


Plate 53 . Recrystallisation around the margin of a large (igneous?) orthopyroxene grain in a pyroxenite .
Crossed nicols . Scale bar 1 mm .

7.4. PYROXENITES

Although pyroxenites are the least abundant members of the ultramafic suite, they are amongst the most interesting since they display some evidence of original igneous textures and also contain relict high pressure mineral assemblages in places.

The majority of these rocks are orthopyroxenites which in many places are associated with diorites and harzburgites, with which they may once have formed a cumulate succession. Websterites (orthopyroxene-clinopyroxene rocks) are much rarer and clinopyroxenites are apparently absent from the study area, although they are reported by Martin (1978) from the Hebron area.

7.4.1. Orthopyroxenites

Orthopyroxenites commonly consist of coarse-grained polygonal aggregates of orthopyroxene, together with variable amounts (10-40%) of pale green amphibole. As in the harzburgites, the amphibole seems to be in complete equilibrium with the orthopyroxene and thus appears to be a primary constituent of the assemblage.

Spinel and iron oxides occur as anhedral blebs which are interstitial to orthopyroxene and amphibole. They are normally present as accessory constituents only, but a few rocks contain up to 10% green spinel. Phlogopite is present in some of the pyroxenites, where it appears to be part of the "primary" assemblage.

A few orthopyroxenites are spectacular very coarse-grained rocks containing porphyroblasts of orthopyroxene up to 2 or 3 cm across. In thin section these rocks appear to partially retain large (igneous?) crystals which are recrystallized around their edges to an aggregate of smaller, polygonal grains (Plate 53). Although it is possible that the large grains represent original igneous phenocrysts, the presence of numerous spinel inclusions is more suggestive of a metamorphic origin.

7.4.2. Websterites

Websterites are rare, but contain some very interesting mineral assemblages. The most notable occurrence is about 1 km south of the western end of Banana Lake, where websterites and hornblendites are associated with amphibolites and leuco-amphibolites of Upernavik type. Contacts between the mafic and ultramafic rocks are sharp and are presumed to be tectonic. The ultramafic rocks are discontinuous along strike, but their precise extent is not known.

The predominant rock type is a coarse-grained, spinel-bearing amphibole-websterite displaying a strong foliation defined by the alignment of amphibole. It consists of about 50% pale green amphibole together with roughly equal amounts of pleochroic hypersthene and pale green, very slightly pleochroic augitic clinopyroxene. These three minerals show every indication of being an equilibrium assemblage; grain boundaries are characteristically straight or curved and show stable 120^{o} interfacial angles and no evidence of reaction relationships is present. Bottle green spinel makes up 2-3% of the rock and occurs as small anhedral blebs which are interstitial to the other constituents.

A smaller proportion of the ultramafic rocks at this locality are garnetiferous, although this is not evident in the field. Consequently, outcrop relationships between garnetiferous and garnet-free websterites are not known, although it is hoped that more information will be obtained in the 1980 field season. The garnet-websterites consist largely (50-60%) of pale-green amphibole similar to that in the garnet-free varieties.

Garnet makes up 5-10% of the rocks and occurs as isolated "islands", which are surrounded by spectacular vermicular intergrowths of spinel, orthopyroxene and plagioclase (Plate 54). The intergrowths appear to be symplectic in origin and plagioclase and orthopyroxene grains are in optical continuity. However, where garnet is in contact with amphibole, symplectic growths are not developed which suggests that amphibole and garnet have remained in equilibrium with one another, and further indicates that amphibole was part of the original garnetiferous assemblages.

Clinopyroxene is a minor constituent of the rocks and only rarely exceeds 5%. Where present, it appears to have been involved in the symplectite-forming reactions, which

Plate 54 . Symplectite composed of spinel (opaque) , orthopyroxene (high relief) and plagioclase (twinned) in a partially retrogressed garnet websterite .
Crossed nicols . Scale bar 1 mm .

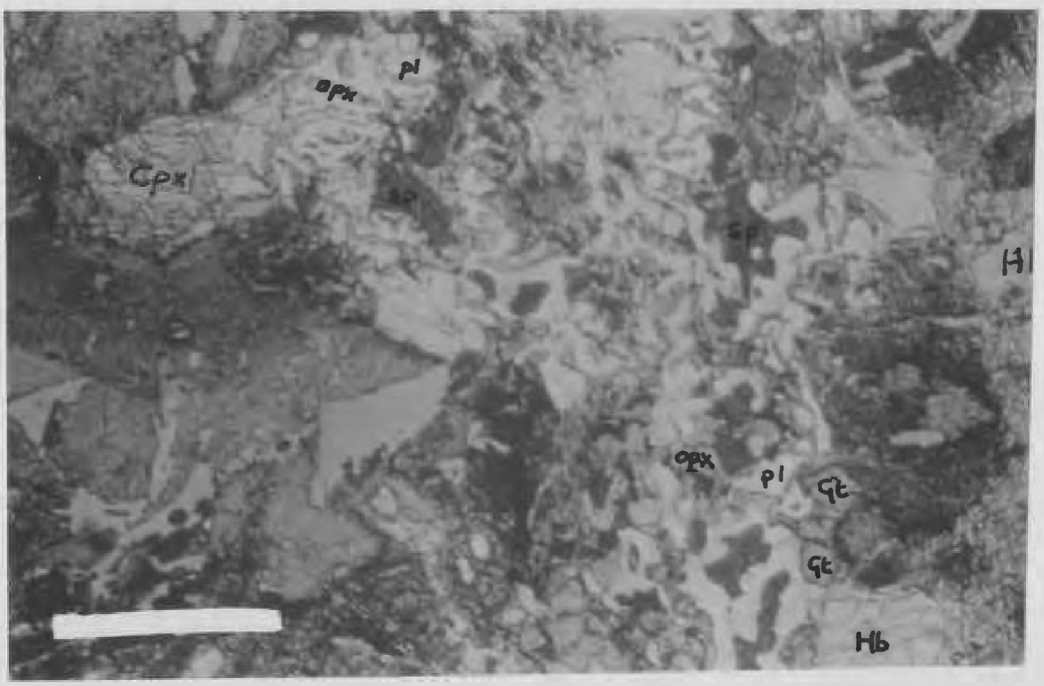


Plate 55 . Zone of symplectite formation between relict garnet (far right) and clinopyroxene(far left) .
This suggest a reaction of the form :

$$Gt + Cpx \rightleftharpoons Opx + Sp + Pl .$$

Plane polarised light . Scale bar 1 mm .

suggests that there might originally have been more clinopyroxene in the rocks under conditions where garnet was stable. The petrographic relationship between garnet and clinopyroxene (Plate 55) suggests a reaction of the form:

Garnet + Clinopyroxene $\rightleftharpoons$ spinel + orthopyroxene + plagioclase

This is similar to the reaction proposed by Leyreloup et al. (1975) in rocks of mafic and ultramafic composition, i.e.

Garnet + Clinopyroxene + Quartz $\rightleftharpoons$ Spinel + Orthopyroxene + Plagioclase

Leyreloup et al. (1975) note that the quartz required for this reaction can either be provided by free quartz or by combined SiO_2 contained in the other reactants. The ultramafic character of the rocks in question suggests that we are dealing with the latter situation. Similar textures are reported from ultramafic rocks in the Swedish Caledonides by Calon (pers. comm. 1979).

These relict garnetiferous assemblages are regarded as further evidence for the allochthonous and allofacial character of the ultramafic rocks. This is consistent with the views of Leyreloup et al. (1975) who consider the above reaction to represent rapid decompression during uplift of the lower crust. It is also consistent with a number of experimental studies (Green and Ringwood, 1967; O'Hara et al. 1971; Irving, 1974; Herzberg, 1978) which suggest that garnet is a high pressure phase in ultramafic rocks. The lower limit of its stability appears to be approximately 17 kbar in peridotites (O'Hara et al., 1971) and 10 kbar in websterites (Herzberg, 1978).

This suggests that the garnetiferous websterites in the study area originally equilibrated at pressures in excess of 10 kb and were later transported to higher levels, probably by thrusting. The original garnet-bearing assemblages were partially retrogressed to spinel-bearing rocks during transport. This interpretation is supported by the lower (7-8 kb) pressures recorded by mineral assemblages in the supracrustal rocks (see Chapter 8).

7.5. SUMMARY

The varied suite of ultramafic rocks described in this chapter retain mineral assemblages which are characteristic of the granulite facies. Their distribution and setting suggests that most of the ultramafic rocks are allochthonous rocks which were interleaved with the supracrustal rocks and the quartzo-feldspathic gneisses by thrusting. However, some of them may originally have formed part of layered mafic-ultramafic intrusions in the Upernavik Suite.

The preservation of garnet-websterites at one locality suggests that, in at least one example, the ultramafic rocks originated at lower crustal levels than the surrounding rocks. The predominant spinel-bearing ultramafic rocks may also represent rocks which originated at greater depths but which were completely retrogressed during upward transport. It is not yet possible to make estimates of the P-T conditions responsible for the generation of garnet-bearing assemblages, but recent experimental work (Herzberg, 1978) suggests that pressures were in excess of 10 kb. A more detailed study of the garnet-websterites and other ultramafic rocks will be presented elsewhere (Collerson and Kerr, in prep.).

CHAPTER 8

METAMORPHISM AND METAMORPHIC CONDITIONS

8.1. INTRODUCTION

The Archean gneisses of the Saglek-Hebron area are polymetamorphic rocks which record the effects of at least three metamorphic episodes. In the context of this thesis, the most important of these events was the largely thermal metamorphism which was broadly contemporaneous with the formation of the Kiyuktok and Ikarut gneisses approximately 2,800 Ma ago. This thermal event was responsible for the generation of these rocks and mineral assemblages formed at that time provide a means of estimating physical conditions.

This chapter is largely concerned with this late Archean metamorphism and is directed at obtaining estimates of metamorphic conditions (i.e. P, T, X_{H_2O}) at that time. Estimates of these variables can be made by a consideration of mineral assemblages and metamorphic reactions or by the use of "geothermometers" and "geobarometers" based upon the compositions of co-existing phases. Both techniques are utilized in this study.

8.2. PRE-2,800 Ma METAMORPHIC EVENTS

Evidence of pre-2,800 Ma metamorphic episodes is only locally preserved. In the Uivak gneisses, rare early granulite facies assemblages are partly retrogressed to amphibolite facies assemblages (see section 5.4 and Collerson and Bridgwater, 1979 for details). Similar early granulite facies assemblages are also preserved in the supracrustal rocks of the Nulliak assemblage (Collerson and Bridgwater, 1979).

The timing of the amphibolite facies metamorphism which retrogressed the early granulite facies gneisses is rather uncertain. However, microstructural features which are believed to represent this episode (section 5.4) are displayed by both Uivak I and Uivak II gneisses, suggesting that this metamorphism was a post-Uivak II event. It is thus possible that amphibolite facies assemblages in the Uivak gneisses and late granulite facies assemblages in the Upernavik supracrustals developed at the same time. The difference in metamorphic grade between the two may simply be a function of bulk compositional differences, and particularly of variations in X_{H_2O}. Alternatively, two or more separate episodes of metamorphism may have been involved.

Evidence for a more complex metamorphic history is preserved on Maidmonts Island, where blocks of layered Uivak I gneiss are present as xenoliths within slightly deformed Uivak II gneisses. These xenoliths contain amphibolite facies assemblages where biotite and hornblende define a fabric. However, this fabric appears to be earlier than a similar fabric in the host Uivak II gneisses, which suggests that retrogression of early granulite facies assemblages at least locally pre-dated emplacement of the Uivak II protoliths.

Evidence of high pressure metamorphism is recorded in some ultramafic rocks which retain garnetiferous assemblages indicative of pressures in excess of 10 kb. This suggests that at least some of the ultramafic rocks are allochthonous, although the timing of their emplacement is not known with certainty. It has been suggested by a number of workers (e.g. Bridgwater et al., 1975; Collerson et al., 1976; Martin, 1978; Collerson and Kerr, in prep.) that the ultramafic rocks were emplaced along tectonic discontinuities developed during the intercalation (by thrusting) of the Uivak gneisses and the Upernavik supracrustal suite.

8.3. LATE ARCHEAN METAMORPHISM

8.3.1. Mineral Assemblages and Reactions

The best indicators of metamorphic conditions are rocks of reactive composition, i.e. mafic and pelitic gneisses. Mineral assemblages in rocks of these compositions are usually characteristic of either the upper amphibolite or granulite facies. In most cases, the assemblages are transitional between the two, and contain both hydrous and anhydrous phases. Thus, in rocks of mafic composition, a typical major mineral assemblage would contain co-existing hornblende, clinopyroxene and orthopyroxene and, in some cases, garnet. Rocks of pelitic composition contain abundant biotite, which co-exists with garnet, sillimanite and orthopyroxene. In virtually all of the supracrustal rocks, hydrous and anhydrous phases appear to be in complete microstructural equilibrium.

Most of the assemblages can thus be assigned to the "hornblende-granulite" sub-facies of DeWaard (1965). This area of P-T-X space represents a field where two dehydration reactions involving hornblende take place in mafic rocks, i.e.:

$$\text{Hb} + \text{Qz} \rightleftharpoons \text{Opx} + \text{Cpx} + \text{Pl} + \text{H}_2\text{O} \qquad (1)$$

$$\text{Hb} + \text{Gt} + \text{Qz} \rightleftharpoons \text{Opx} + \text{Pl} + \text{H}_2\text{O} \qquad (2)$$

In pelitic and semi-pelitic rocks, the hornblende-granulite sub-facies is represented by reactions involving the breakdown of biotite, i.e.:

$$\text{Bi} + \text{Qz} \rightleftharpoons \text{Opx} + \text{Gt} + \text{K-fsp} + \text{H}_2\text{O} \qquad (3)$$

$$\text{Bi} + \text{Sill} + \text{Qz} \rightleftharpoons \text{Gt} + \text{K-fsp} + \text{H}_2\text{O} \qquad (4)$$

In rocks which contained staurolite as part of their amphibolite facies assemblage, two other reactions may also apply, i.e.:

$$\text{St} + \text{Qz} \rightleftharpoons \text{Gt} + \text{Sill} + \text{H}_2\text{O} \qquad (5)$$

$$\text{St} + \text{Qz} \rightleftharpoons \text{Cd} + \text{Sill} + \text{H}_2\text{O} \qquad (6)$$

(Richardson, 1968)

Reaction (5), which forms garnet, takes place at higher pressures than the cordierite-generating reaction (6).

All of these reactions have two features in common; (1) they all require the participation of SiO_2 and (2) they all liberate varying amounts of H_2O.

They are thus not only dependent upon ambient pressure and temperature, but are also affected by the activity of silica (a SiO_2) and by X_{H_2O}. The effect of increasing X_{H_2O} is to shift the univariant reaction curves to higher temperatures. For example, reaction (1) takes place at about 1100°C at 10 kb if $P_{H_2O} = P_{LOAD}$ but occurs at only 700°C if $P_{H_2O} = 0.1\ P_{LOAD}$ (e.g. Wells, 1979). Similar relationships hold for the other reactions (e.g. DeWaard, 1965; Richardson, 1968; Wells, 1979).

In mafic gneisses within the study area, there is a highly irregular distribution of amphibolite (opx-free) and granulite facies mineral assemblages. In many areas, there is apparent variation in metamorphic grade within single outcrops. Samples from individual domains within outcrops are, however, in complete microstructural equilibrium. The apparent variation in metamorphic grade in these examples is considered to reflect local variations in X_{H_2O}, rather than local variations in P-T conditions (c.f. Buddington, 1963).

In silica-deficient rocks, reactions (1) and (2) will be strongly affected by the amount of available SiO_2. Once this is consumed, further breakdown of hornblende will be impossible regardless of P-T conditions. This may explain the rarity of true mafic pyroxene granulites within the study area, since rocks of this composition are likely to be silica-deficient under granulite facies conditions.

Evidence of metamorphic reactions is relatively rare in the rocks. Reaction (2) is recorded in a number of metagabbroic rocks which contained early garnet and the presence of graphic Opx-Pl growths in some garnet-free rocks suggests that it may have proceeded to completion. The generation of orthopyroxene from biotite is recorded in some semi-pelitic rocks; this may reflect reaction (3) or a reaction of the form:

$$\text{Bi} + \text{Qz} \rightleftharpoons \text{Opx} + \text{K-fsp} + H_2O \quad (7)$$

(Turner, 1968).

However, the many uncertainties involved in the reactions which govern the hornblende-granulite facies make it impossible to make reliable temperature estimates without a knowledge of X_{H_2O}, which obviously varied upon both a regional and local scale. Temperature estimates obtained from co-existing mineral pairs (section 8.3.2) are between 750°C and 850°C. Since the rocks in question contain anhydrous and hydrous phases, these represent equilibrium assemblages developed by the boundary reactions (1) to (6). In the case of reaction (1), temperatures of this range suggest H_2O-undersaturated conditions where $P_{H_2O} = 0.1\text{-}0.2\ P_{LOAD}$ (Wells, 1979; fig. 12). Water contents of this order seem quite reasonable for both rock types.

The presence of garnet in granulite facies rocks has been advanced as an indicator of high pressures (e.g. Buddington, 1963; Green and Ringwood, 1967; Green, 1970).

However, there is also evidence which suggests that the presence of garnet is to some extent a function of bulk composition. Specifically, it has been shown by DeWaard (1965) and Manna and Sen (1974) that garnetiferous amphibolites and granulites have higher Fe/Mg ratios and lower CaO contents than their non-garnetiferous equivalents.

These conclusions are certainly supported by field observations in the study area, where garnet is preferentially concentrated into discrete layers which are believed to represent compositional variation in the protoliths. Such a regular, alternating distribution of garnet in individual outcrops is clearly inconsistent with variations in pressure.

In most of the mafic gneisses in the study area, garnet is a late phase which occurs as large poikiloblastic crystals containing inclusions of hornblende, clinopyroxene and orthopyroxene. In some instances, garnet is present as an early phase which is replaced by plagioclase and orthopyroxene. This suggests the operation of reaction (1), i.e.:

$$\text{Gt} + \text{Hb} + \text{Qz} \rightleftharpoons \text{Opx} + \text{Pl} + H_2O$$ (DeWaard, 1965).

Late garnet porphyroblasts could form by a number of reactions, notably:

$$\text{Hb} + \text{Pl} + \text{Qz} \rightleftharpoons \text{Cpx} + \text{Gt} + H_2O \quad (8)$$

(Carmichael, 1974)

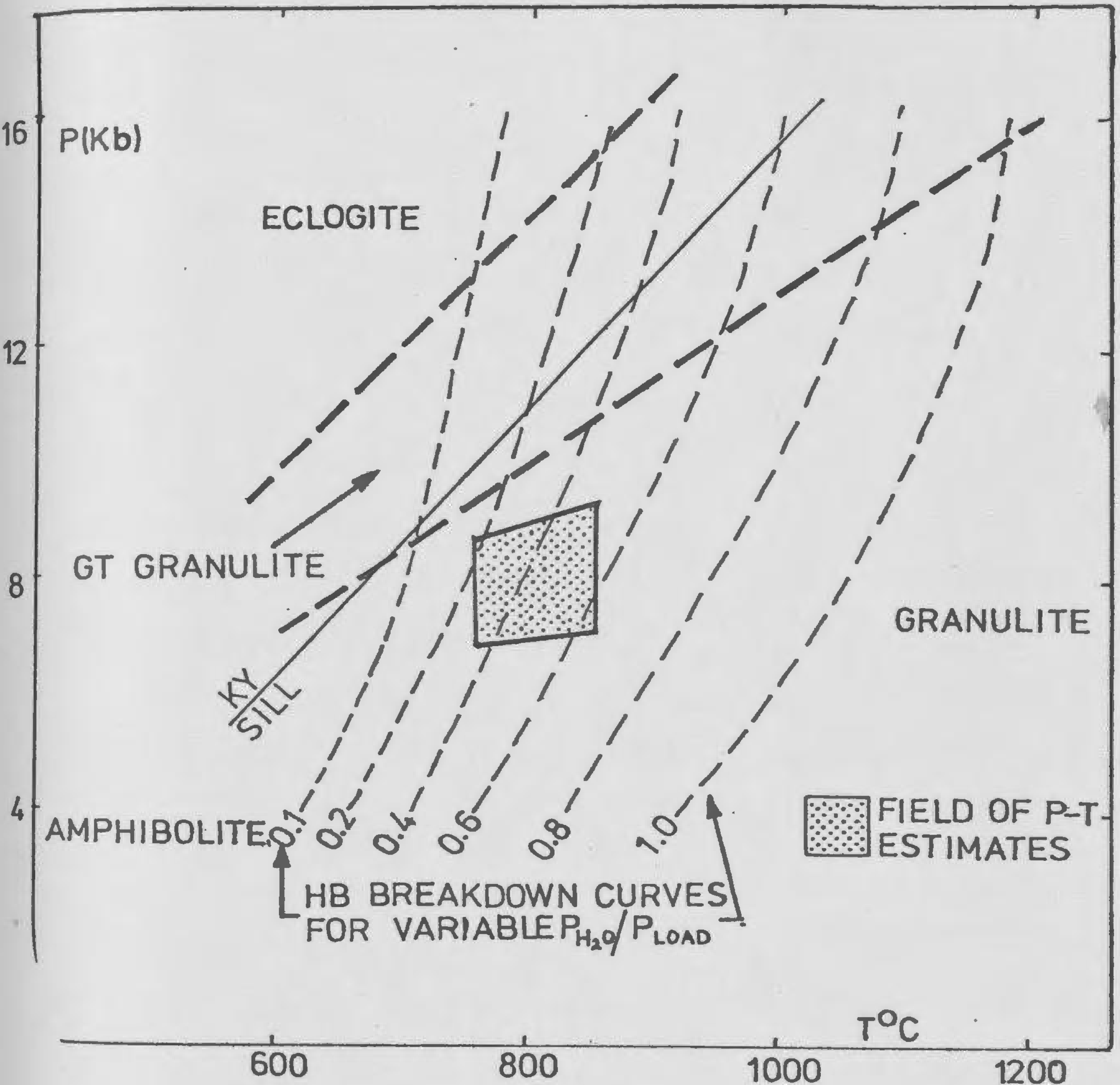


Figure 12 . P-T Estimates for the study area derived by geothermometry and geobarometry . Garnet-granulite field from Green and Ringwood(1967) and Kyanite-Sillimanite phase diagram from Richardson et al.(1969) . Hornblende breakdown curves from Wells (1979) .

and Opx + Pl $\rightleftharpoons$ Cpx + Gt + Qz (9)

(DeWaard, 1965; Manna and Sen, 1974).

Manna and Sen (1974) suggest that reaction (9) may be coupled with the normal hornblende breakdown reaction, i.e.:

Hb + Qz $\rightleftharpoons$ Opx + Cpx + Pl + H_2O (1)

(DeWaard, 1965)

Orthopyroxene and plagioclase released by hornblende breakdown react to form garnet, clinopyroxene and quartz, with the quartz assisting further hornblende breakdown.

The formation of garnet by reaction (9) is possible by either isobaric cooling or an increase in pressure (Fig. 12), or a combination of both. However, even if cooling is assumed, ambient temperatures would still be high enough to allow the breakdown of hornblende.

Garnet in pelitic and semi-pelitic rocks is normally produced via the breakdown of biotite via reactions (3) and (4), or from staurolite by reaction (5). Garnet and cordierite-bearing assemblages are related by the reaction:

Cd $\rightleftharpoons$ Gt + Sill + Qz (10) (Hensen, 1971).

This reaction has received extensive experimental study (Hensen and Green, 1973; Currie, 1971; Hensen, 1977) and appears to be largely dependent upon pressure. Garnet-bearing assemblages are typical of high pressures, whereas cordierite-bearing assemblages reflect relatively low pressures. Garnet and cordierite co-exist in the presence of quartz and sillimanite at intermediate pressures.

The position and width of the field where both minerals co-exist is largely dependent upon the bulk Fe/(Fe+Mg) ratio of the rocks. However, the distribution of Mg^{2+} and Fe^{2+} between garnet and cordierite in any one rock is a function of pressure and temperature alone, which has led to the use of this reaction as a geothermometer and a geobarometer (Hensen, 1977; Wells, 1979). The experimental results of Hensen (1977) suggest that the upper pressure limit for cordierite stability is between 6 and 10 kb, depending upon bulk Fe/(Fe+Mg) ratios. In typical pelites and semi-pelites (Fe/Fe+Mg = 0.4-0.6), cordierite and garnet would co-exist between 5.5 and 9 kb at temperatures between 750°C and 850°C.

Garnet-cordierite assemblages are quite common in the study area which suggests moderate pressures. Metamorphic temperatures are harder to estimate since the breakdown of biotite is strongly affected by Fe/(Fe+Mg) ratios and by X_{H_2O} (Turner, 1968) and takes place over a wide temperature range. Fairly extensive migmatization in pelitic supracrustal units suggests temperatures in excess of 700°C.

8.3.2. Geothermometry and Geobarometry

(i) Methods:

A consideration of major mineral assemblages in the supracrustal rocks allows broad estimates of metamorphic conditions to be made. More precise estimates can be made by the application of a number of modern "geothermometers" and "geobarometers", which form the subject of this section.

Derivation of P-T estimates from the compositions of co-existing mineral phases is only possible if the mineral assemblages in question have attained chemical equilibrium. Criteria for the recognition of equilibrium assemblages are (1) absence of mineral zoning, (2) granoblastic textures with polygonal grain shapes and (3) regular distribution of cations between the various phases. The internal consistency of estimates made using different mineral pairs can also be used as an indicator of equilibrium.

It is obvious that the microstructural criteria for equilibrium are satisfied by the Upernavik supracrustal lithologies, which display very little evidence of metamorphic reaction and generally show well-developed granoblastic polygonal textures. Mineral analyses from widely separated grains in individual samples are completely consistent and there is no significant compositional zoning. These rocks thus appear to be ideal subjects for geothermometry and geobarometry.

A number of geothermometers and geobarometers have been proposed in recent years and several individual methods have been applied in this study. Temperatures were estimated from co-existing clinopyroxene and orthopyroxene (Wood and Banno, 1973; Wells, 1977) and from co-existing garnet and clinopyroxene (Raheim and Green, 1974; Wells, 1979; Ellis and Green, 1979; Saxena, 1979) in rocks of mafic composition.

In rocks of pelitic composition, the distribution of Fe^{2+} and Mg^{2+} between garnet and cordierite (Hensen, 1977; Wells, 1979) was utilized. A recent method using garnet and biotite (Ferry and Spear, 1978) was used in a few examples.

Estimates of pressure were obtained using the garnet-orthopyroxene method of Wood (1974) and the garnet-cordierite method of Wells (1979) in rocks of mafic and pelitic composition respectively.

The thermodynamic basis for the calibration of geothermometers and geobarometers is dealt with by Wood and Fraser (1976) and Greenwood (1977) and will not be discussed here. For details of individual methods, and for details of the many assumptions involved in calibration, the reader is referred to the specific publications listed above. This section is intended merely to present data, and critical evaluations of the various methods, such as those presented by Bohlen and Essene (1979), will not be attempted here.

A number of representative samples were selected for electron microprobe analysis and representative mineral analyses are presented in Table 6.* Analysis was carried out with a JEOL JXA 50A electron probe microanalyzer incorporating a Krisel disk control system with alpha corrections. Analyses in Table 6 are averages of at least 10 spots within each grain. Recalculation of mineral analyses was accomplished with a computer program devised by Cawthorn and Collerson (1974) and using the technique of Ryburn et al. (1975).

*See Appendix.

(ii) Results:

Geothermometry and geobarometry calculations for each of the techniques listed above were carried out using a Hewlett-Packard programmable calculator and programs devised by K. D. Collerson. Results are tabulated in Table 7. Many of the geothermometry calculations (e.g. Raheim and Green, 1974; Ellis and Green, 1979; Wells, 1979; Saxena, 1979) require pressure assumptions. The results shown in Table 7 were derived using pressure assumptions of 7 kb, which are consistent with results obtained from garnet-cordierite geobarometers and with the absence of kyanite. The effects of varying the assumed pressure were tested and found to be negligible over a pressure range from 5 to 15 kb.

The consistency of individual techniques is variable. The most internally consistent results are obtained with the methods of Wood and Banna (1973), Wells (1979) and Saxena (1979). The methods of Raheim and Green (1974) and Ellis and Green (1979) are much less consistent and, as a group, give lower temperatures than any of the other techniques. The garnet-biotite geothermometer of Ferry and Spear (1978) seems to give unreasonably high temperatures for two Kiyuktok gneisses, but this may be due to problems in analyzing biotite, which is intergrown on a very fine scale with epidote and quartz in these rocks.

Despite the wide range of results, the majority of the temperature estimates fall in the range from 750°C to

Table 7: Temperature estimates for various Upernavik supracrustal rocks.

SAMPLE	CPX-OPX WOOD & BANNO 1973	CPX-OPX WELLS (1977)	GT-CPX RAHEIM AND GREEN (1974)	GT-CPX ELLIS AND GREEN (1979)	GT-CPX WELLS (1979)	GT-CPX SAXENA (1979)	GT-CORD WELLS (1979)	ASSEMBLAGE
AK-78-51A	818	802						Cpx-Opx-Hb-Pl
AK-78-115B	806	790						Cpx-Opx-Hb-Pl
AK-78-115C	815	805						Cpx-Opx-Hb-Pl
KC-74-554	823	872	686	841	757	790		Cpx-Opx-Hb-Pl-Gt
KC-77-507A	783	823	567	592	647	818		Cpx-Opx-Gt-Sp
KC-77-507B	756	786						Cpx-Opx-Gt-Sp
AK-78-262	840	872						Cpx-Opx-Pl-Qz-Bi
AK-78-270B	824	862	710	690	791	865		Cpx-Opx-Pl-Hb-Gt
AK-77-53			593	788	676	777		Cpx-Gt-Pl
KC-76-4100			740	906	840	847		
AK-77-47B			635	671	722	819		Cpx-Gt-Hb-Pl
AK-78-32A			659	682	750	836		Cpx-Gt-Hb-Pl
KC-78-4629			705	750	801	779		Cpx-Gt-Opx
AK-78-271			682	659	775	865		Cpx-Gt-Qz
AK-78-116							661	Qz-Pl-Mi-Opx-Cd-Bi-Sill

Table 8 . Preliminary pressure estimates for the study area obtained by the garnet-cordierite method of Wells(1979) .

ASSUMED TEMPERATURE (^{o}C)	600	700	800	900
LOWER LIMIT	7.2Kb	7.3Kb	7.5Kb	7.6Kb
UPPER LIMIT	7.8Kb	8.2Kb	8.6Kb	9.0Kb

Based upon average analyses from samples AK-78-116A and AK-78-116B .

850^{o}C (Fig. 13a). If the estimates obtained by the internally inconsistent methods of Raheim and Green (1974) and Ellis and Green (1979) are not considered, the peak in the histogram at 750^{o}C-850^{o}C is even more apparent (Fig. 13b).

Pressure estimates obtained by the garnet-cordierite method of Wells (1979) are shown in Table 8. Although this is based only upon two samples, it suggests a range in pressure of 7.2 kb - 8.9 kb, depending upon the assumed temperature of equilibration. The garnet-orthopyroxene geobarometer of Wood (1974) produced rather inconsistent results and could only be applied to orthopyroxenes in a narrow compositional range. Problems were also encountered in calculation, which suggests some unresolved difficulties in data treatment. For this reason, results obtained with this method are not presented here.

Further work needs to be conducted to obtain more numerous pressure estimates via the method of Wells (1979). When obtained, these will hopefully be presented elsewhere (Collerson and Kerr, in prep.) and combined with a critical evaluation of the various techniques used in this study.

8.4. SUMMARY AND DISCUSSION

Mineral assemblages within the study area mostly belong to the transitional field between amphibolite and granulite facies (hornblende-granulite sub-facies of DeWaard, 1965) and are believed to represent assemblages in

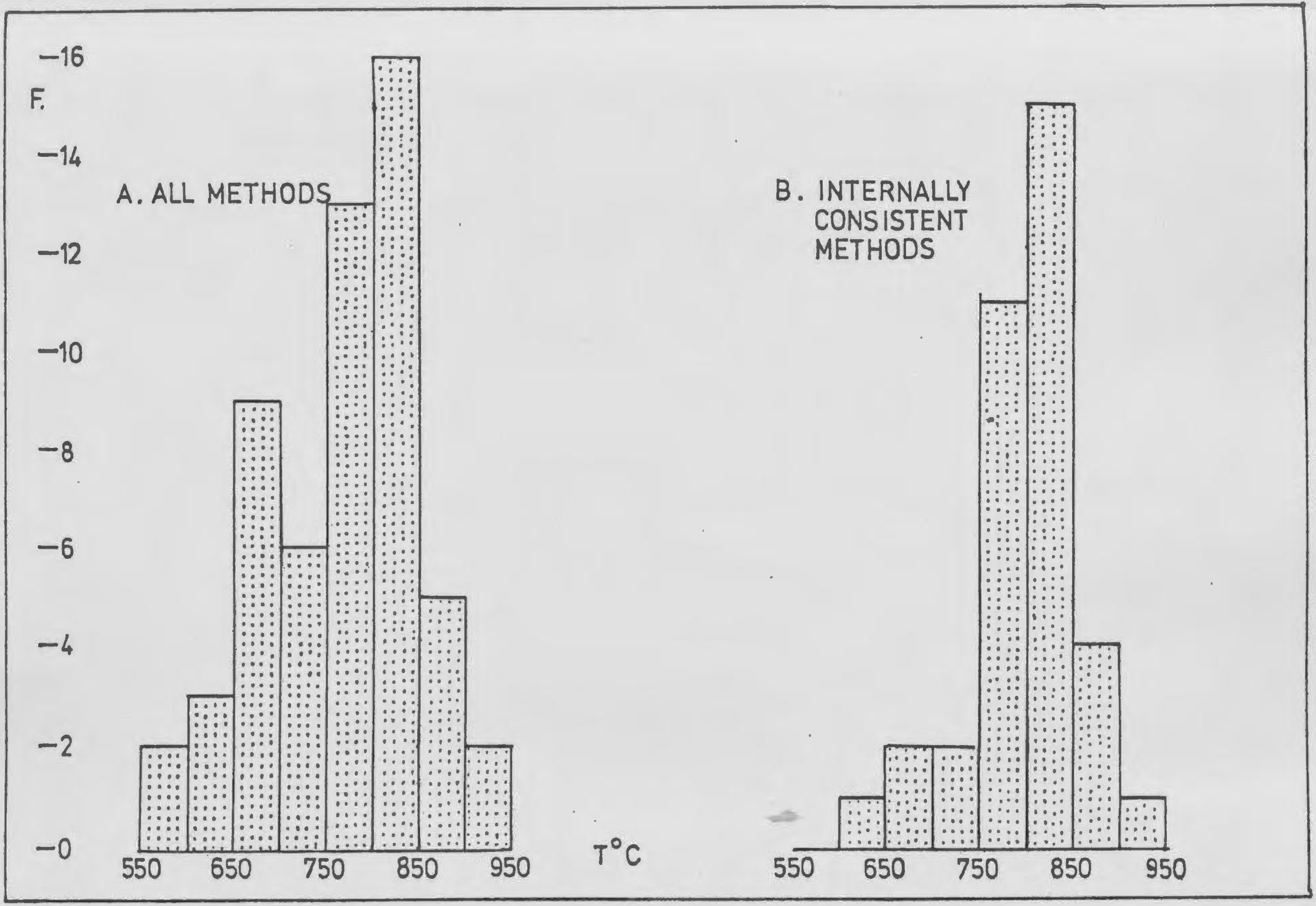


Figure 13 . Histograms showing the frequency distribution of temperature estimates . (A) All Methods (B) Internally consistent methods .

varying states of dehydration. The apparently irregular, and often outcrop-scale variation in the relative proportions of hydrous and anhydrous phases is thus attributed to local variations in X_{H_2O}, and not to variations in physical conditions.

Virtually all of the assemblages appear to represent chemical equilibrium, as evidenced by polygonal granoblastic microstructures, consistency of mineral compositions and lack of mineral zoning.

Estimates of temperature made using the compositions of co-existing mineral pairs are variable and range from 600-950°C. However, most of the results fall in the range 750°C-850°C and, if the internally inconsistent results obtained by the Raheim and Green (1974) and Ellis and Green (1979) techniques are disregarded, 85% of the results are in the range 750-900°C. The average value for all of the internally consistent results (n = 37) is 804°C, and for all results (n = 55), 769°C.

Pressure estimates obtained by the garnet-cordierite method of Wells (1979) suggest a range of 7.2-8.9 kb which is consistent with the absence of kyanite and the co-existence of garnet, cordierite, sillimanite and quartz.

The partial pressure of water can be estimated from the hornblende-breakdown reaction and the P-T estimates derived by geothermometry and geobarometry. Simple amphibole component equilibria for cummingtonite and tremolite were extended for natural systems by Wells (1979), using the mixing models of Wells (1976) and Powell (1975). The resultant curves for varying values of P_{H_2O} are shown in Fig. 12, together with P-T estimates. Since most of the mafic gneisses in the study area are at hornblende-granulite facies, they represent assemblages developed on the hornblende-breakdown curve for a particular set of P-T conditions. This reasoning suggests that P_{H_2O} was between 0.3 and 0.5 of P_{LOAD} in hornblende-bearing (i.e. mafic) compositions (Fig. 12).

Under these P_{H_2O} conditions, and at temperatures of 750-850^{o}C rocks of quartzofeldspathic composition (i.e. the Uivak gneisses) would not undergo significant melting (Wyllie, 1977). This clearly contradicts evidence from field relations, petrology and geochemistry which suggests extensive melting during the formation of the Kiyuktok gneisses (Chapter 5). In order to accommodate this melting, we must postulate either a higher initial water content in the Uivak gneisses, or some input of water from an outside source. This possibility will be discussed further in the final chapter.

The P-T estimates derived in this study suggest a geothermal gradient of c. 35-40^{o}C/km, which is higher than the 25-30^{o}C/km gradients suggested by similar studies of equivalent rocks in Greenland and Northwest Scotland (O'Hara, 1977; Wells, 1979).

CHAPTER 9

STRUCTURAL GEOLOGY

9.1. INTRODUCTION

One of the initial objectives of this study was to develop a structural chronology and to relate this to the igneous and metamorphic events which occurred during Late Archean times. Although these objectives were only partly realized, the structural evolution of the study area is interesting in the light of discussions concerning the preponderance of horizontal or vertical tectonic regimes during the Archean (Bridgwater *et al.*, 1974; Myers, 1976; Bridgwater and Collerson, 1977; Glikson, 1977; Chadwick and Coe, 1975; 1976).

The structural analysis of polydeformed high-grade metamorphic rocks is fraught with problems and, before proceeding to a more detailed treatment of the study area, it is necessary to first discuss some of these difficulties. The review which follows is directed specifically to Archean high-grade complexes such as the study area and West Greenland, but is applicable in most respects to younger gneissic terrains.

9.2. STRUCTURAL ANALYSIS OF HIGH-GRADE GNEISSIC TERRAINS

The evolution of the Archean gneiss complexes in West Greenland and coastal Labrador took place over a period of at least 1300 Ma (Bridgwater *et al.*, 1974; Collerson *et al.* 1976; Collerson and Compston, in prep.). In view of these extended periods of tectonic activity, it is hardly surprising that the structural and metamorphic evolution of these areas is a complex and difficult topic.

The regional structural grain of these gneissic terrains is dominated by an anastomosing pattern formed by the superimposition of several generations of structures, the earliest of which appear to have been largely coaxial. Although this pattern is extremely complex, it is usually only a reflection of the later deformational episodes in a long and complex sequence. The layering which defines these interference structures is itself a composite feature which developed via a number of deformational episodes which are now represented only by intrafolial structures.

This exemplifies one of the greatest problems in the analysis of gneissic terrains; i.e. the near-total "destruction" of early structures and original chronological relationships by later intense deformation. This is largely a result of the reorientation of earlier planar elements by repeated isoclinal folding (transposition). This was accompanied by other processes such as metamorphic differentiation and pegmatite injection which caused the obliteration of earlier structures and contributed to the formation of a new layering. As a result of transpostion, rock types of different ages and origins are interleaved conformably on both a regional and local scale. This regional layering behaves in a manner analogous to that of a stratigraphic sequence where affected by later large-scale structures.

However, high-grade gneissic terrains are characterized by rapid lateral variations in the intensity of deformation (e.g. Coward, 1973a, b; Zwart, 1960; Park, 1969; Collerson et al., 1976). As a result of this heterogeneity of deformation, original relationships and early structures are preserved in a few small enclaves. The reasons for the preservation of these enclaves of relatively low intensity deformation are presently uncertain. It may be a result of competence contrasts between different rock types under high-grade metamorphic conditions. This has been suggested by Coward (1973a, 1973b) who relates the persistence of small Archean relics within the Laxfordian (Proterozoic) belts of Scotland to the "strengthening" effect of massive amphibolite horizons within the quartzofeldspathic gneisses.

Competence contrasts may also be related to water content as anhydrous rocks are usually much less ductile and may resist deformation to a large extent (e.g. Watson, 1973; Bell and Etheridge, 1976). Within largely anhydrous areas, deformation is mostly concentrated into prominent lineaments which are known as "straight belts" (Watson, 1973).

Within the Archean gneiss complex of the Saglek-Hebron area, enclaves of relatively weak deformation are often situated in the hinge zones of relatively early mega-scopic tight to isoclinal folds. This is true of the crucial areas on Maidmonts Island, Mentzel Island and Big Island (Collerson, pers. comm.) and also at Fire Cove and Kiyuktok

Cove within the study area. These enclaves appear to have resisted much of the later deformation and metamorphism. The reasons for the localization of such enclaves in early fold closures are not at all clear, although it is possible that most of the later strain was absorbed by the more strongly anisotropic rocks along the limbs.

Although this heterogeneity of deformation has allowed reconstruction of the early history of many gneissic complexes, and particularly those of the North Atlantic area, it causes a number of problems in structural analysis.

Rapid lateral variations in the magnitude of strain causes an equally rapid variation in the appearance of certain rock types (e.g. Myers, 1970, 1978) and causes severe difficulties in field work and may lead to problems in the tracing of marker horizons. The local preservation of early megascopic structures leads to problems in the correlation of successive fold episodes because superficially similar overprinting relationships in separate areas may actually be of quite different ages. This illustrates one of the problems which is inherent in the use of "fold style" (i.e. symmetry, morphology and orientation) in the analysis of polydeformed rocks (e.g. Park, 1969; Williams, 1970).

Park (1969) has suggested that the most reliable criteria for the establishment of overprinting relationships are fabrics and foliations, which can often be related to particular metamorphic conditions and thus identified with more confidence. If these fabrics are axial planar to particular groups of structures, some correlations between fold episodes can then be made.

However, in polycyclic gneisses which have been subjected to repeated high-grade metamorphism, fabrics of radically different ages may have exactly the same characteristics. Further problems arise in quartzofeldspathic gneisses where shape fabrics predominate over mineral fabrics. Shape fabrics cannot be created or destroyed by recrystallization and are therefore re-oriented into parallelism with younger structures (i.e. transposed) or completely destroyed. Consequently, overprinting relationships between shape fabrics cannot exist because only one shape fabric is possible at any time (Watterson, 1968).

The use of small-scale structural patterns as a "guide" to the regional development of polycyclic gneisses is also of questionable value. Many of the complex small-scale interference patterns which develop in migmatitic rocks may be "flow" folds of the type described by Wynne-Edwards (1963) and may not be particularly relevant to the structural history of the rocks. Even where clear examples of superimposed minor folds exist, they may simply reflect local complexities in the deformation path.

The identification and correlation of linear elements suffers from similar problems and several possibilities usually exist for the age and origin of any one lineation (Park, 1969).

Furthermore, lineations do not usually display any consistent orientation, which may reflect variation in local extension directions, extensive refolding, or a combination of these factors.

9.3. STRUCTURAL ANALYSIS OF THE STUDY AREA

The problems reviewed in the previous section make any attempt at reconstructing the structural evolution of the study area an intrinsically difficult task. The treatment of structural geology contained in this section is thus largely qualitative and is based upon an analysis of the macroscopic structural patterns revealed by regional mapping. The approach suggested by Park (1969) has been used; the earliest penetrative planar element is labelled S_N and the successive folding episodes which affect it are designated F_{N+1}, F_{N+2}, F_{N+3}, etc., etc. The development of the Kiyuktok and Ikarut gneisses provides an important marker and allows the identification of pre-Kiyuktok and post-Kiyuktok structures.

For the purposes of description, the study area is split into two structural blocks, which are separated by the Middle Cove fault zone. The western block evolved via the superimposition of a number of large fold structures of both pre-Kiyuktok and post-Kiyuktok age. Structural patterns in the eastern block are more obscure and are discussed in a separate section (9.3.4.).

9.3.1. S_N -- The Regional Layering

The earliest penetrative planar structure recognizable on a regional scale is referred to as the "regional layering" and is designated S_N. This is a composite feature defined by a number of individual elements of different ages which are described below. S_N is affected by a number of later folding episodes and forms a valuable reference point in the deformation sequence. F_N is regarded as the deformation episode which brought S_N to its present state, while the first phase of folding which clearly affects S_N is termed F_{N+1}.

S_N is defined by a number of discrete elements ranging in scale from microscopic to macroscopic, including some elements whose length and thickness is measured in kilometres. In order of increasing scale we can identify the following elements:

(1) A gneissic ("migmatitic") layering defined by the alternation of leucocratic and melanocratic bands in the Uivak I gneisses. This is usually parallel to a mineral foliation defined by biotite and/or hornblende and a shape fabric defined by quartz and feldspar.

(2) A strong porphyroclastic fabric (augen gneissosity) developed in the Uivak II gneisses.

(3) A lithological layering defined by the alternation of deformed Saglek dykes and Uivak gneisses.

(4) A large-scale lithological layering on a scale of hundreds of metres or even kilometres which is defined by

alternating units of Uivak gneiss, mafic gneiss, pelitic and semi-pelitic metasediments and by conformable lenses of ultramafic material. In the case of the supracrustal rocks, internal compositional layering is normally parallel to the large-scale alternation of lithological units.

Throughout virtually all of the area, these four principal planar elements are parallel. Only in certain small enclaves of relatively weak deformation (Maidmonts Island, Big Island and Mentzel Island) can the development of S_N through geological time be documented.

The earliest planar element involved in S_N is undoubtedly the "migmatitic" layering in the Uivak I gneisses. This, however, is itself a composite feature as numerous rootless intrafolial folds are enclosed by the layering. These cannot be correlated and may be of many different ages (i.e. F_N, F_{N-1}, F_{N-2}, etc. etc.).

In certain outcrops on Mentzel Island, strongly layered Uivak gneisses containing numerous intrafolial folds are cut by relatively homogeneous porphyritic granitic rocks which are regarded as parents to the Uivak II gneisses. Over most of the area, however, the strong porphyroclastic fabric in the Uivak II gneisses is parallel to the Uivak I migmatitic layering. This implies that S_N (defined in both units) in most areas is a product of post-Uivak II events which also re-oriented an earlier composite layering in the Uivak I gneisses.

In most areas, concordant Saglek dykes are parallel to both augen gneissosity and migmatitic layering and thus define S_N (Plate 7a). However, intrusive relationships between Saglek dykes and deformed Uivak gneisses are preserved in enclaves of low intensity deformation. This implies that further post-Saglek dyke deformation must have taken place in order to bring the dykes and the earlier planar elements into parallelism.

Original relationships between the Upernavik supracrustals and the Uivak gneisses are not preserved, but the absence of Saglek dykes in the former suggests that they are younger than the Uivak gneisses and the Saglek dykes. The supracrustal rocks are believed to have accumulated upon a Uivak gneiss basement between 3400 and 3200 Ma ago (Collerson et al., 1976). Since they are now interleaved concordantly with the earlier gneisses, and now define a large-scale layering which parallels the elements described above, further intense deformation must have occurred after their formation. Similar arguments apply to the ultramafic units which are also younger than the Saglek dykes.

S_N is thus a composite layering which involved at least five separate deformational episodes over a period of over 200 Ma. The earlier planar elements within S_N have been re-oriented into parallelism with later fabrics by repeated transposition. Associated processes such as metamorphic differentiation, anatexis and pegmatite injection may also have acted to obliterate early fabrics and create new ones.

9.3.2. Pre-Kiyuktok Events

The formation of the Kiyuktok gneisses and the emplacement of the temporally equivalent Ikarut and Kammarsuit gneisses (Collerson, Kerr and Compston, 1980) is an important reference point in the structural analysis of the area. The reactivation of the Uivak gneisses to form the Kiyuktok gneisses obliterated earlier structures affecting S_N and a group of pre-Kiyuktok structures can thus be identified. Later (post-Kiyuktok) structures are of more restricted extent and cause the development of moderate to strong fabrics in the Kiyuktok gneisses which are broadly axial planar to the later structures.

Macroscopic structures of pre-Kiyuktok and syn-Kiyukton age are best displayed in the Fire Cove belt and at Kiyuktok Cove itself. The former area provides the most complete sequence of events.

The Fire Cove belt (see geological map and Fig. 14) is an elongate structure some 10 x 4 km in outcrop area composed of partly reactivated Uivak gneisses, mafic gneisses and pelitic to psammitic metasediments. The central part of the belt is a refolded fold structure (type III of Ramsay, 1969) containing a core of well-preserved Uivak II gneisses. Two smaller structures, which appear to be intrafolial to S_N,

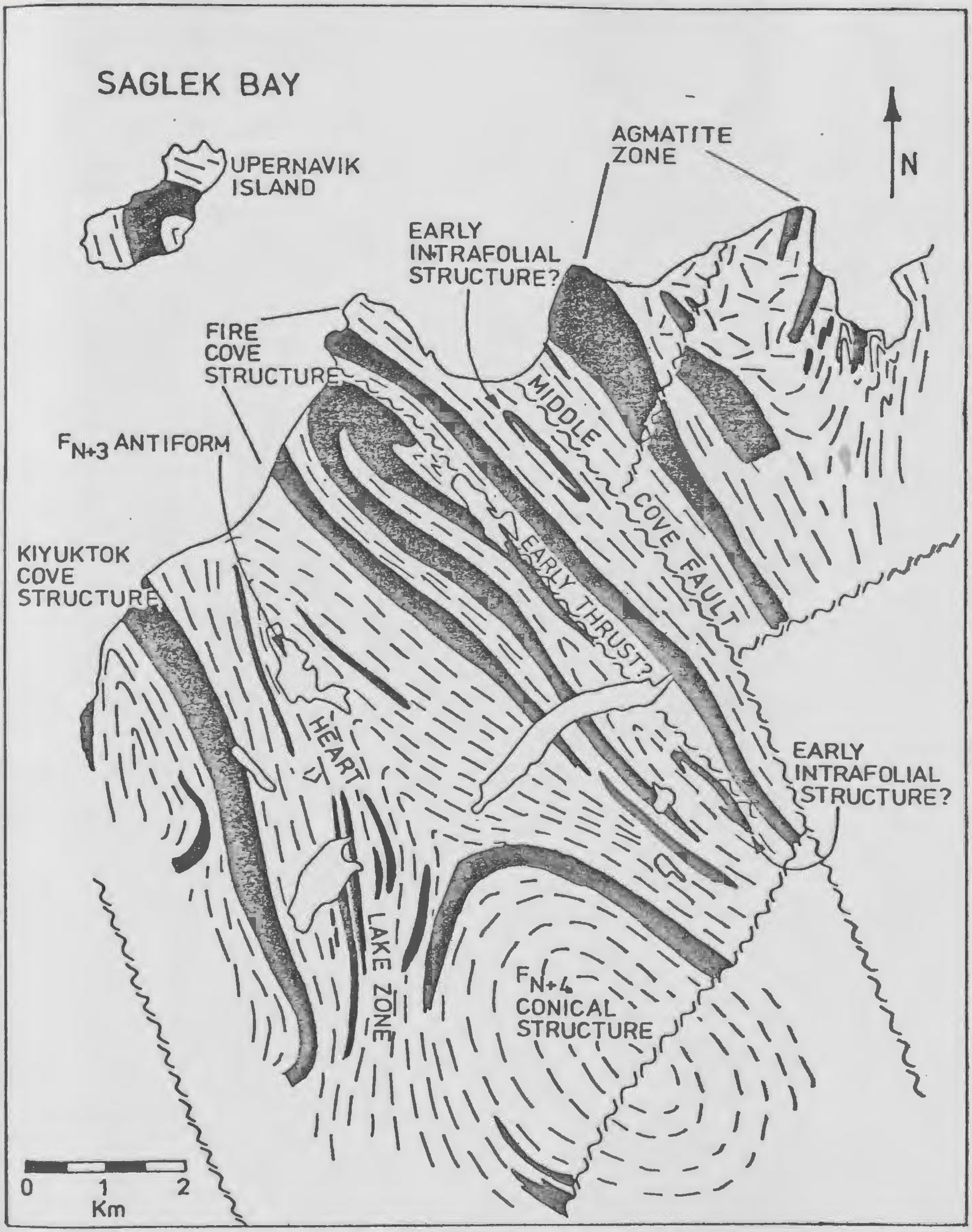


Figure 14 . Structural trends in the study area , which are defined by supracrustal units and the gneissic layering (S_N) .

outcrop along the eastern flank of the belt. These are regarded as the earliest structures and are described first.

(i) F_N or Pre-F_N Structures:

F_N is regarded as the folding episode which produced the present regional layering known as S_N. Fold closures representing F_N (or earlier episodes such as F_{N-1}, F_{N-2}, etc.) would only be preserved as rootless structures which are intrafolial to S_N. Two structures of this type are preserved along the eastern flank of the Fire Cove belt (Fig. 14).

The more northerly example (close to Middle Cove) appears to consist of a paired synform and asymmetric antiform which appear to be discontinuous along strike. This is interpreted as a doubly-plunging structure whose axial plane is parallel to S_N.

A similar structure about 1.5 km south of the east end of Banana Lake appears to be a doubly-plunging intrafolial antiform.

The absolute age of these intrafolial structures is not known. However, as they are intrafolial to S_N they must represent F_N or some earlier episode. They do, however, post-date the interleaving of the supracrustal rocks and the Uivak gneisses because they fold a layering defined by both. The layering preserved in the hinge zones of these folds is actually S_{N-1} or some earlier feature, but is materially the same as S_N, which was produced by its re-orientation during F_N.

(ii) F_{N+1} and F_{N+2} Structures:

Structures representing these two episodes of folding are present in the type III interference pattern forming the central part of the Fire Cove belt. The axial trace of the earlier fold is believed to lie within the core zone of Uivak II gneisses. This axial trace is refolded by a second generation isoclinal fold whose axial trace appears to be truncated by a prominent fault and thus cannot be traced further south. The axial planes to both structures appear to be vertical or near-vertical.

The exact three-dimensional form of the Fire Cove structure is difficult to establish since the regional layering is vertical or near-vertical in most outcrops. However, the coastline southwest of Fire Cove exposes pelitic and semi-pelitic gneisses which dip southeastward at angles between 30° and 60°. This suggests that the Fire Cove structure is a result of the superimposition of two tight to isoclinal synforms to produce a composite structure similar to that shown in Fig. 15. Due to the similarity in the style of the two folds, it is impossible to separate F_{N+1} and F_{N+2} outside of areas where they are seen to interfere.

The Fire Cove belt is a good example of the type of complex structure which commonly occurs in high-grade polydeformed terrains. It is part of the process whereby the regional layering (S_N) is being re-oriented to lie parallel to the axial planes of F_{N+2} folds. This re-orientation is

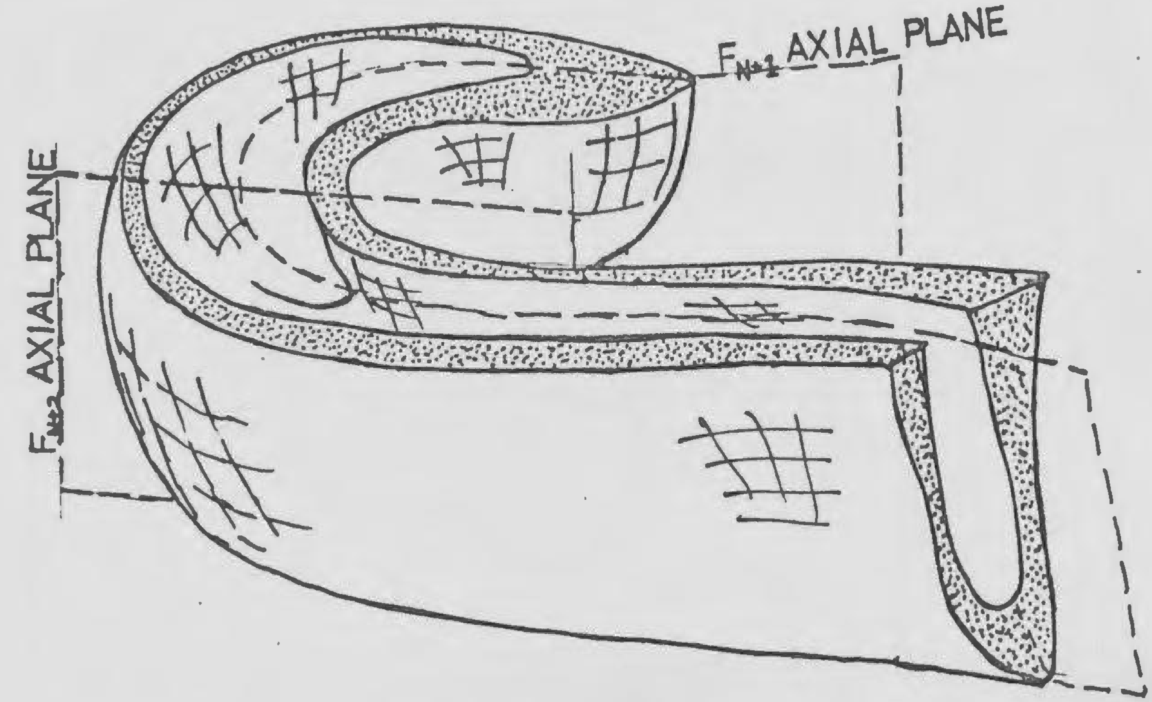


FIG. 15 PROBABLE FORM OF THE FIRE COVE STRUCTURE

almost complete in the Fire Cove area, and original relationships between S_N and the axial traces of F_{N+1} and F_{N+2} folds are preserved only in the hinge zones. However, if these fold closures were not preserved, only a large-scale regional layering would exist which would be indistinguishable from S_N as we have defined it. Consequently, correlation between different areas of the gneiss complex using S_N as a reference point may be misleading because the regional layering is not necessarily of the same age in all areas.

A tight to isoclinal antiform of broadly similar age to the Fire Cove structure is exposed at Kiyuktok Cove. This is separated from the Fire Cove structure by a later post-Kiyuktok antiform and a prominent shear zone, but it is possible that the two might once have been laterally continuous (see section 9.4).

The hinge zone of the Kiyuktok Cove antiform displays some interesting relationships between the development of the Kiyuktok gneisses and the folding. In this area, both _in situ_ and intrusive Kiyuktok components in the gneisses obliterate and truncate "M" folds which are parasitic upon the larger structure. In other nearby areas, however, layers and lenses of reworked material are strongly boudinaged and/or folded. The small folds which are responsible for this deformation are also interpreted as parasitic upon the larger structure. If this inference is correct, it suggests that the development of the Kiyuktok gneisses was at least partially coeval with this particular folding event. The Kiyuktok Cove antiform is thus a syn-Kiyuktok fold. It is therefore tempting to suggest that this structure is a later feature than either F_{N+1} or F_{N+2}, which do not show comparable relationships with the Kiyuktok gneisses, and appear to be completely pre-Kiyuktok structures. An alternative explanation is that the reactivation of the Uivak gneisses was diachronous with respect to the folding, or vice versa.

As can be seen from the above discussions, identification and correlation of pre-Kiyuktok structures is very difficult upon local or regional scales. Nevertheless, we can make some statements concerning the nature and intensity of pre-Kiyuktok deformation.

(1) The style of folds appears to be tight to isoclinal, and similar in all examples.

(2) Several generations of folds can be recognized although identification and correlation of individual examples is not always possible.

(3) The axial planes of the folds are generally vertical or near vertical and parallel to the regional lithological layering (S_N). Only in the hinge zones are overprinting relationships preserved.

(4) The later episodes of folding were at least locally contemporaneous with the reactivation of the Uivak gneisses to form the Kiyuktok gneisses.

9.3.3. Post-Kiyuktok Events

Events which post-dated the formation of the Kiyuktok gneisses led to the production of a number of important structures within the study area. Areas where post-Kiyuktok structures exist are characterized by the development of a moderate to strong foliation in the Kiyuktok gneisses which, in some cases, is axial planar to the folds themselves.

There are potentially two phases of folding of post-Kiyuktok age which are designated F_{N+3} and F_{N+4} respectively. An elongated zone of intense deformation within which Upernavik supracrustal rocks are extensively disrupted (the Heart Lake zone) contains strongly deformed Kiyuktok gneisses and is thus regarded as a post-Kiyuktok structure.

The final stages in the evolution of the gneiss complex were marked by the emplacement of post-tectonic granites and diabase dykes and by extensive block faulting. These were to some extent contemporaneous, but dyke emplacement probably continued until Phanerozoic times (e.g. Hyndman, 1973).

(i) F_{N+3} Structures:

The most important structure of this age is a tight, upright antiform which plunges northward at 20-30° and is well-exposed at Bob's Pond (see map). The closure is well displayed by the regional layering (S_N) which is defined in this area by the outcrop pattern of mafic gneisses, psammitic gneisses and quartzites. Kiyuktok gneisses within the sequence display a strong foliation which is defined by the elongation and alignment of glomeroporphyroblastic aggregates ("clots") of biotite. This mineral foliation is broadly parallel to the axial plane of the antiform and intersects the regional layering (S_N) at low to moderate angles. It is regarded as an S_{N+3} fabric. A moderate to strong foliation defined by biotite alignment and cataclastic fabrics in some of the Ikarut gneiss sheets is also attributed to this phase of folding.

The western limb of the F_{N+3} antiform can be traced along strike into the Heart Lake zone, which is described below.

(ii) The Heart Lake Zone:

The gneisses within the Heart Lake zone are a group of multicomponent rocks which are characterized by three components (Plates 56A, 56B):

(1) Pods and lenses of mafic and ultramafic material;

(2) A strongly-foliated quartzofeldspathic matrix; and

(3) Numerous concordant sheets of coarse-grained granitic pegmatite.

The inclusions are the most obvious components and constitute 15-50% of the rocks by volume. About 75% of the

(a)

(b)

Plate 56 a,b . Typical strongly deformed multicomponent gneisses from the Heart Lake Zone . Note numerous inclusions and concordant pegmatite sheets .

inclusions are of mafic composition, and the remainder are mostly ultramafic, although metasedimentary inclusions exist in a few areas. The size of individual pods and lenses is highly variable; they range from small stringers and lenses to mappable units several hundred metres or more in length. In terms of shape, they range from recognizably lensoid objects to highly oblate spheroids whose shape is comparable to that of a disc. A strong preferred orientation amongst the inclusions defines an S-fabric whose visibility in the outcrop surface depends largely upon orientation with respect to the fabric. Inclusions often line up along strike (Plate 57) suggesting that they are boudinaged fragments of originally continuous units. Some inclusions contain discordant internal fabrics (Plate 58) which may be relics of structures developed during earlier deformational episodes.

The quartzofeldspathic material which forms the matrix is variable in appearance. In places it displays a strong compositional layering defined by biotite-rich zones. In other areas, however, it has a "streaky" appearance caused by highly elongate clots of biotite. In a few areas rocks which appear very similar to Uivak I migmatitic gneisses or deformed Kiyuktok gneisses can be recognized.

Some fairly extensive bodies of Upernavik supracrustal rocks are present within the zone. The most obvious of these is known as the "Heart Lake Remnant" and consists of interlayered pelites, semi-pelites and mafic gneisses. Several

Plate 57 . Boudinaged mafic inclusion in the Heart Lake Zone . 2 km S.E. of Heart Lake .

Plate 58 . Amphibolite inclusion with a discordant internal fabric suggestive of a complex early history . 2 km S.E. of Heart Lake .

large bodies of mafic gneiss and ultramafic material outcrop further to the east (see map). The contacts between these supracrustal units and the quartzofeldspathic gneisses are especially interesting. In most cases, the proportion of inclusions within the gneisses increases rapidly towards the contact through a transitional zone up to 100 m wide. Smaller scale relationships of identical type are preserved around some of the larger inclusions (Plate 59).

This seems to suggest that the numerous slivers of mafic and ultramafic gneiss in the Heart Lake zone were derived by the disruption of more extensive supracrustal sequences. This disruption may have been related to the emplacement of granitic material (c.f. Myers, 1976) or may reflect dismemberment by folding and/or intense boudinage. It is also possible that both processes occurred.

It is proposed here that the Heart Lake zone is a belt of intense deformation which represents the site of a disrupted synform which was once adjacent to, and complementary to the antiform at Bob's Pond. The disruption of the synform and the supracrustal sequences is inferred to have taken place via simple shear, which was sufficiently intense to include a large component of shortening perpendicular to the XY plane of the finite strain ellipsoid for the shear zone, thus explaining the shape of the inclusions. It remains possible, however, that some disruption of supracrustal sequences by igneous processes (i.e. the formation of the

Plate 59 . Margin of a large mafic inclusion near Heart Lake . This type of relationship suggests that disruption by igneous injection may have preceded intense deformation in the Heart Lake Zone . The pegmatitic material in this example resembles typical Kiyuktck gneisses and contains clots of biotite with garnet cores .

Kiyuktok gneisses and the emplacement of the Ikarut gneisses) may have taken place prior to shearing. The presence of rocks which appear to represent strongly deformed Kiyuktok gneisses indicates that shearing was a post-Kiyuktok event. The large amounts of concordant pegmatitic material in the Heart Lake zone is of uncertain origin. It does not resemble intrusive Kiyuktok gneisses and may perhaps represent later pegmatites which were emplaced synchronously with shearing in the Heart Lake zone but are discordant in other parts of the area.

(iii) F_{N+4} Structures:

One of the most obvious structures in the study area is a prominent "eye" fold between Banana Lake and Bracelet Lake. This is a tight, antiformal structure whose form is best described as "conical" and which dips outward at angles between 50^o and 80^o. When traced to the north, this structure is seen to form part of the F_{N+3} antiform described above. This suggests that the development of the conical structure is a result of the refolding of the F_{N+3} structures by later, more open folds whose axial planes intersect those of the earlier folds at high angles. The effect of this cross-folding by F_{N+4} was to open out the earlier antiforms at particular points. "Basinal" structures complementary to these cones did not form because F_{N+3} synforms are not preserved.

Chadwick and Nutman (1979) describe similar tight conical structures from the Buksefjord region of West Greenland which are flanked by steep shear zones containing much pegmatite. These appear to be analogous to the F_{N+3} + F_{N+4} structures suggested above. However, they do not attribute them to cross-folding but instead propose that they were generated during a single phase of folding which would appear to correspond with F_{N+3} in the study area.

In the absence of any clear independent evidence of cross-folding, this explanation might also apply to the study area; further work is needed before any preferred interpretation can be made.

9.3.4. Structures Within the Eastern Block

Structural patterns in the area to the east of the Middle Cove fault zone are not as well defined as in the Western block and are more difficult to interpret. In terms of dominant rock types, it can be divided into three sub-divisions.

In the Middle Cove area, it is dominated by a thick sequence of Upernavik mafic gneisses and metasediments which are interleaved with Uivak gneisses. The Torr Bay area is dominated by slightly reworked Uivak gneisses which contain some small units of supracrustal material.

Between Torr Bay and Middle Cove, the area is underlain by vast quantities of agmatitic rocks formed by the disruption of the gneisses by granitoid material of probable

"Ikarut" age. This entire area is devoid of coherent structural patterns and cannot be interpreted with confidence; although some "ghost" folds may exist.

The earliest structures in the Eastern block are probably those preserved in the Uivak gneisses at Torr Bay. A well-developed "migmatitic" layering is present in these outcrops and the presence of numerous intrafolial folds suggests that this is itself a composite feature. This layering, which here defines S_N, is affected by a series of tight to isoclinal folds whose axes are coast-parallel and plunge at angles up to 20^o in a southerly direction. The emplacement of Kiyuktok pegmatites seems to post-date the development of the folds, suggesting that they are broadly correlative with F_{N+1} and F_{N+2} in the Western block.

The Upernavik supracrustal rocks at Middle Cove display a symmetrical arrangement which is highly suggestive of repetition by folding. Direct evidence for the existence of these folds is lacking, but a complex interference structure is developed upon the headland east of Middle Cove. This involves at least three generations of folds (Collerson, pers. comm.), but the relationship between these events and the formation of the Kiyuktok gneisses is not known.

The agmatitic area in the central part of the eastern block is largely devoid of coherent structure. The age of agmatite development is not known at present and this matter awaits an isotopic study of the "granitoid" leucosome in the near future. It is possible, however, that the extensive agmatite development in this area is one of the effects of the Kiyuktok-Ikarut event. If this is so, the disruption of supracrustal sequences in the Heart Lake zone prior to intense deformation may have been related to a similar process (c.f. Myers, 1976).

9.3.5. Faulting and Emplacement of Late Intrusive Rocks

The study area is cut by a number of faults which are marked in the field by zones of mylonitization and large amounts of pervasive brick red pegmatite.

The Middle Cove fault zone is the most important structural discontinuity as it separates an area in which the Uivak gneisses were extensively reworked (the Western block) from one in which they were only slightly affected.

Granulite facies rocks appear to be more widespread in the Western block than in the Eastern block, which suggests that the former may represent a deeper crustal level. This is consistent with the more extensive reworking of the Western block.

The Middle Cove fault zone is sub-parallel to a major fault known as the Handy fault zone running through St. John's Harbour. This fault zone separates an area of amphibolite facies rocks from the transitional amphibolite-granulite and granulite facies rocks of the study area (Bridgwater *et al.*, 1975). Its sense of movement thus appears

Plate 60a . The massive , undeformed centre of a diabase dyke near Heart Lake . This dyke was emplaced into a late fault zone .

Plate 60b . Margin of the above dyke . Note strong fabric development.

to be the same as that of the Middle Cove fault zone and the two structures are probably related.

This fault, and most of the other faults in the study area, cut earlier structures at high angles and thus represent late features in the evolution of the area. At least some of the fault movements appear to have been partly contemporaneous with the intrusion of diabase dykes which display schistose margins containing greenschist facies mineral assemblages. These schistose margins contrast strongly with the massive interiors of the dykes (Plate 60). In other instances massive, unaltered dykes occupy mylonitic fault zones, suggesting that movement had ceased by the time the dykes were emplaced.

The emplacement of late pegmatites and granites also appears to be related to faulting to some extent and most fault zones contain pervasive stockworks of a brick red quartz-K-feldspar pegmatite.

9.4. DISCUSSION AND INTERPRETATION

The previous sections have outlined some of the problems involved in structural analysis of high-grade metamorphic rocks and described the structural patterns in the study area. This section attempts to integrate the structures described in section 9.3 into an overall structural synthesis to explain the outcrop pattern shown in the geological map.

The schematic cross-section which accompanies this report is considered to represent the most likely structural geometry in a plane perpendicular to the regional structural grain of the study area.

The F_{N+3} antiform at Bob's Pond is the central structure in the study area and is flanked on either side by earlier structures (F_{N+1} and F_{N+2}) in the Fire Cove belt and at Kiyuktok Cove. The Heart Lake zone is believed to have developed on the site of a disrupted synform which was originally complementary to the central F_{N+3} antiform.

In view of the demonstrably different ages of the structures within the study area, it seems reasonable to assume that structural trends established during earlier events were modified by F_{N+3} folding. The cross-section proposes that the gross lithological layering defined by the limbs of F_{N+1} and F_{N+2} tight to isoclinal folds was once continuous across the more open F_{N+3} antiform, but was disrupted extensively in the Heart Lake zone. The closures of the earlier generations of folds are preserved in the Fire Cove belt and at Kiyuktok Cove.

Since the Kiyuktok Cove antiform lies on the other side of the Heart Lake zone, its original relationship to the broadly equivalent Fire Cove structure is uncertain. It is possible that it was once continuous with the structures in the Fire Cove belt as part of a composite structure similar to the "nappes" identified by Chadwick and Nutman

(1979) in the Buksefjord region of West Greenland.

This type of structural pattern is most easily explained in terms of an early sub-horizontal layering which has been extensively rotated by later structures with sub-vertical axial planes. Comparable structural patterns in West Greenland have been interpreted in a similar fashion (Berthelsen, 1960; McGregor, 1973; Bridgwater et al., 1974; Chadwick and Nutman, 1979). However, it has also been pointed out that an early sub-vertical layering could result from the modification of a basement-cover relationship by isoclinal folds with sub-vertical axial planes (Glikson, 1977; Calon, pers. comm.). Whilst this concept is certainly valid in a general sense, several lines of evidence mitigate against its applicability in this particular case.

Firstly, there is absolutely no evidence to suggest that any of the present contacts between the Upernavik supracrustals and the Uivak gneisses represent deformed unconformities. Indeed, the sharp nature of these contacts and the intense deformation in immediately adjacent rocks is much more consistent with a tectonic origin. In this context, possible early thrusts responsible for the interleaving of basement and cover have been recognized by Chadwick and Nutman (1979) in the Buksefjorden region of Southwest Greenland. In the study area, a prominent zone of intense deformation and mylonitization which forms part of the "stratigraphy" in the Fire Cove belt probably represents an early thrust zone developed during the later stages of pre-Kiyuktok deformation.

Secondly, the occurrence along such zones of clearly allochthonous ultramafic units with relict high-pressure mineral assemblages suggests that the supracrustal rocks may also be allochthonous.

A third argument against the concept of vertical layering lies in the intense flattening or elongation observed in early lithologies. It is very difficult to envisage regional extension on a scale of 50 : 1 in a vertical sense without an incredible degree of crustal thickening (Bridgwater et al., 1974; Bridgwater and Collerson, 1977). Although there are still problems in accommodating these strains within a horizontally-layered crust (Glikson, 1977), they are minor compared to those encountered by the first hypothesis.

In view of the above arguments, it is suggested that the earliest events in the evolution of the area were dominated by repeated thrusting and recumbent isoclinal folding. The regional layering (S_N) was developed at an early stage by (1) interleaving of basement and cover via thrusting, and (2) associated transposition of earlier planar elements (S_{N-1}, S_{N-2}, etc.). Early fold closures (F_{N+1}, F_{N+2}) within the Fire Cove belt are evidence of further recumbent folding and thrusting which re-oriented this layering over large tracts, but did not transpose it completely in the study area.

All of the above processes are consistent with a deformational regime in which simple shear was the dominant mechanism (Escher and Watterson, 1974; Bridgwater et al., 1974).

Relationships in the Kiyuktok Cove area suggest that the formation of the Kiyuktok gneisses was at least locally contemporaneous with the later phases of recumbent deformation. In most other areas, however, the Kiyuktok gneisses post-date early folds, but pre-date the tight, upright structures characteristic of later events. These post-Kiyuktok events involved (1) the development of tight, upright antiforms causing substantial rotation of earlier structures and (2) the formation of steep zones of intense deformation (e.g. Heart Lake zone) where supracrustal sequences were extensively disrupted. These zones are interpreted as sheared F_{N+4} synforms, which may also previously have been sites of agmatite development during the magmatic events responsible for the formation of the Kiyuktok and Ikarut gneisses. This interpretation is supported by the existence of a less deformed agmatite zone of similar age at Torr Bay, which probably represents a higher level in the complex.

Agmatite zones of this type would be much less resistant to deformation than surrounding rocks and would be natural loci for the initiation of shear zones.

It is therefore concluded that the structural

FIGURE 16 .(OPPOSITE) . A HIGHLY SCHEMATIC DIAGRAM ILLUSTRATING THE PROPOSED STRUCTURAL EVOLUTION OF THE STUDY AREA

(A) . Early sub-horizontal or low angle layering formed by thrusting and/or recumbent isoclinal folding leading to the intercalation of the Uivak gneisses and the Upernavik supracrustals .

(B) . Tight folding around vertical axial planes during F_{N+3} events . Reorientation of earlier flat-lying structures into near-vertical attitudes . Development of strong fabrics in some Kiyuktok and Ikarut gneisses.

(C) . Disruption of F_{N+3} synforms and development of steeply dipping shear zones (e.g. Heart Lake Zone) where supra-crustal sequences are extensively disrupted . Strong planar fabrics developed in these zones .

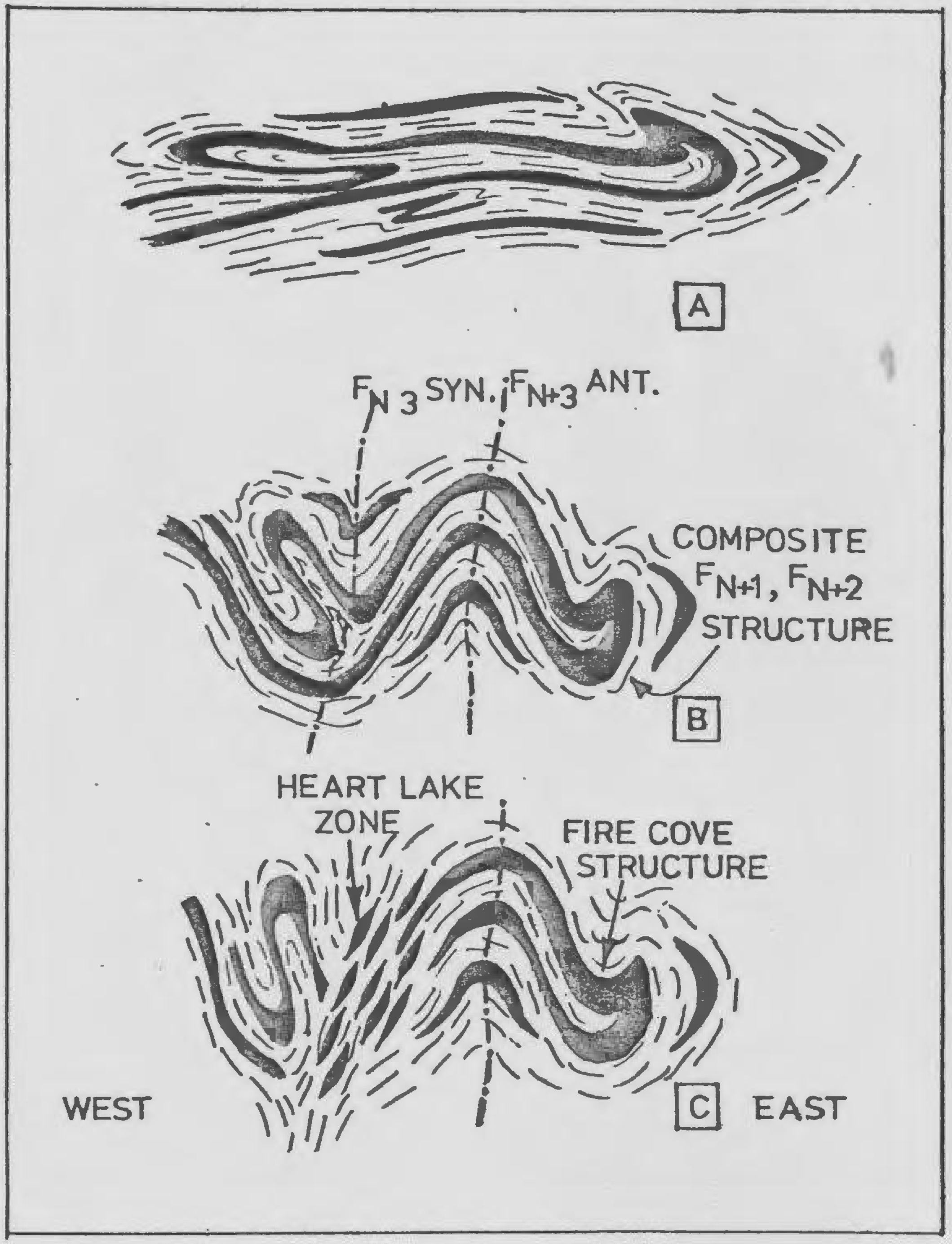

A
F N 3 SYN.
F N+3 ANT.
COMPOSITE
F N+1, F N+2
STRUCTURE
B
HEART LAKE
ZONE
FIRE COVE
STRUCTURE
WEST
C
EAST

Figure 16 .

evolution of the study area is explicable in terms of:

(1) early sub-horizontal movements resulting in thrusting and recumbent isoclinal folding;

(2) later vertical movements, with differential motion between zones of uplift being largely absorbed in steep shear belts initiated in structurally "weak" zones of granitoid injection and agmatite development. This is shown schematically in Fig. 16.

This scheme is in accord with the views of Bridgwater et al. (1974), Chadwick and Coe (1974, 1976), Myers (1976) and Chadwick and Nutman (1979). However, the existence of early sub-horizontal structures does not automatically imply a "horizontal tectonic regime" of the type proposed by Bridgwater et al. (1974). It is also possible that the earliest horizontal movements were themselves a result of larger-scale vertical movements (c.f. Ramberg, 1967) caused by gravitational instabilities.

CHAPTER 10

LATE ARCHEAN CRUSTAL DEVELOPMENT

10.1. INTRODUCTION

This thesis has dealt with a number of different aspects of the Late Archean evolution of the study area, but is aimed specifically at the problem of "crustal reworking" during Late Archean events. This final chapter is intended to serve two purposes. Firstly, it provides an opportunity to briefly summarize some of the evidence dealt with in previous chapters which pertain to the early history of the complex. The second aim of this chapter is a more in-depth treatment of the Late Archean rocks, the Kiyuktok, Ikarut and Kammarsuit gneisses. Models are presented for the generation of these rocks and evaluated in the light of theoretical and experimental petrology. An attempt is also made to integrate these models into a single model for Late Archean crustal development in Northern Labrador and some of the implications of this study are discussed.

10.2. CRUSTAL DEVELOPMENT PRIOR TO 3,000 Ma AGO

Although this thesis is aimed at an investigation of Late Archean events, some knowledge of the early Archean rocks is essential if the "reworking" hypothesis outlined in Chapters 3-5 is to be evaluated. Certain aspects of this early history are discussed in detail in previous chapters (5.2, 5.3, 5.4, 6.4, 7.5, 9.4), and by Collerson *et al.* (1976)

and Collerson and Bridgwater (1979). A brief review of pre-3,000 Ma crustal development is presented below, and is intended as a framework for the following discussion of later events.

The most widespread group of pre-3,000 Ma rocks are the Uivak gneisses (Bridgwater and Collerson, 1976; Collerson and Bridgwater, 1979), which underlie 70-80% of the early Archean enclave east of the Handy fault zone. The Uivak gneisses are dominantly layered, migmatitic gneisses of trondhjemitic, tonalitic and granodioritic composition (Uivak I gneisses) which are interleaved with, and locally cut by subordinate amounts of "granitic" augen gneisses (Uivak II gneisses). The field relations and petrology of these rocks is discussed in detail in 3.2, 4.2 and 5.4, and by Collerson and Bridgwater (1979). Their development took place over a time interval of at least 250 Ma and involved several discrete events.

Initially, a suite of tonalitic to granodioritic intrusive rocks (Uivak I protoliths) was emplaced into an early terrain dominated by ultramafic and mafic material (Nulliak assemblage). The ultimate origin of the Uivak I protoliths is open to question; however, the most likely mechanism is the partial melting of mafic source rocks under a high geothermal gradient (Barker and Arth, 1976; Collerson and Fryer, 1978; Collerson and Bridgwater, 1979; McGregor, 1979; Glikson, 1979). Melting of anhydrous (granulite facies) parents would yield H_2O-undersaturated magmas with liquidus temperatures in excess of 1000°C, which would be capable of digesting vast quantities of country rock (c.f. Glikson, 1979).

The subsequent production of the Uivak I migmatitic gneisses is envisaged as a result of simultaneous anatectic melting and intense deformation (5.3, Fig. 6), perhaps as a result of solidus depression concomitant with water addition as a result of xenolith dehydration (c.f. Glikson, 1979) or simply as a consequence of post-emplacement granulite facies metamorphism (Collerson and Bridgwater, 1979). The author is thus in full accord with the views of Myers (1970, 1978) regarding the production of banded gneisses by the deformation of heterogenous igneous rocks. The more potassic, Fe-rich Uivak II augen gneisses are probably also products of partial melting of the earlier trondhjemite-tonalite suite (Collerson and Bridgwater, 1979).

Development of the Uivak I migmatites and emplacement of the Uivak II protoliths was followed by emplacement of a swarm of diabase dykes (Saglek dykes) which are seen to cut both groups of rocks.

The remaining 20-30% of the pre-3,000 Ma gneiss complex is composed of supracrustal rocks which form part of the Upernavik suite. The rocks are of variable composition, but are dominated by pelitic to psammitic metasediments and mafic gneisses, with subordinate quartzites and calc-silicates. They are described in detail in Chapter 6. The Upernavik supracrustal suite is considered to represent a volcano-sedimentary assemblage which developed on top of, or adjacent to, an earlier Uivak gneiss-Saglek dyke basement complex.

The present disposition of the two groups of rocks requires that they be interleaved in some fashion to form the regional layering (S_N) which responds to later events. Although evidence is far from conclusive (9.4), the nature of Uivak gneiss-supracrustal contacts and the intensely anisotropic fabrics developed in both rock types suggest that their intercalation was largely a product of recumbent isoclinal folding and thrusting in a structural regime dominated by simple shear (c.f. Bridgwater et al., 1974; Escher and Watterson, 1974; Myers, 1976). This is envisaged to have involved (1) early thrusting and (2) later recumbent folding to produce large-scale structures such as those at Fire Cove. These processes would certainly have caused some degree of crustal thickening, and resulted in the formation of a crust characterized by low-angle or sub-horizontal layering.

To summarize, the following statements can be made concerning the nature of the pre-3,000 Ma crust:

(1) It was dominantly (70-80%) trondhjemitic to tonalitic in composition, with subordinate

granitic components.

(2) These quartzofeldspathic gneisses had undergone repeated metamorphism at an earlier stage and were therefore depleted in L.I.L. elements and volatiles.

(3) 20-30% of the crust was composed of supracrustal rocks which were presumably at relatively low grades of metamorphism and thus water-rich compared to the polymetamorphic quartzofeldspathic gneisses.

(4) The crust had recently undergone some degree of crustal thickening caused by the tectonic intercalation of the Uivak gneisses and the Upernavik supracrustals.

10.3. THE NATURE OF LATE ARCHEAN EVENTS

Late Archean events can be divided into essentially three categories: (1) the reworking of the Uivak gneisses to form the Kiyuktok gneisses, (2) the formation and emplacement of Late Archean intrusive rocks (e.g. the Ikarut and Kammarsuit gneisses), and (3) the high-grade metamorphism of the pre-3,000 Ma rocks, notably the Upernavik supracrustals.

These three aspects of Late Archean crustal evolution are intimately related in time and space and it seems unlikely that they are independent of one another. It seems most logical to regard them as manifestations of a single thermal event, speculations as to the nature of which will be presented in a later section. However, for the purposes of this discussion, it is best to treat them separately.

10.3.1. The Formation of the Kiyuktok Gneisses

The reworking of the Uivak gneisses was one of the most important effects of Late Archean thermal events and represents the most significant finding of this thesis. The field relations and petrology of the Kiyuktok gneisses (5.5, 5.6, 5.7) provide compelling evidence for the reworking of the Uivak gneisses by partial melting and mobilization. Evidence from Rb-Sr and Pb-Pb isotopic systems is presented in Collerson et al. (1980) and provides conclusive evidence for crustal reworking. Although Sr isotopic systems were reset at c. 2,800 Ma, Pb-Pb results indicate a precursor age of c. 3,500 Ma, which must surely represent the Uivak gneisses. The high initial Sr isotope ratio (0.7086) displayed by the Kiyuktok gneisses is entirely consistent with derivation from a sialic source.

The progressive development of the Kiyuktok gneisses can be explained in terms of progressive partial melting of the Uivak gneisses. Melts incorporated quartz, K-feldspar and the albitic portion of plagioclase and their formation was enhanced by the breakdown of biotite to yield orthopyroxene and water (5.7). The principal residual phase was plagioclase which is present as strained grains of "Uivak" morphology and composition (An_{20-25}) in most Kiyuktok gneisses. Variation in the extent of melting gives rise to a continuous series of rocks ranging from recognizable Uivak gneisses containing irregular patches of "melt" to partially mobile nebulites and, ultimately, to fully mobilized intrusive pegmatites. Lithological similarities between these rocks and the earliest "melt" fractions in transitional rocks suggest that these intrusive pegmatites resulted from partial melting of the Uivak suite. Their ternary minimum composition (5.8) is also consistent with such an interpretation. The presence of relict garnet in these pegmatites may indicate the participation of metasedimentary material in their petrogenesis (c.f. Green, 1976; White and Chappel, 1977).

(i) Physical Constraints:

In order to investigate the melting of the Uivak gneisses further, metamorphic conditions were studied by a variety of qualitative and quantitative methods presented in Chapter 8. Although results were somewhat scattered, most estimates of temperature fall between 750°C and 850°C, irrespective of pressure assumptions. Estimates from garnet-cordierite pairs suggest pressure between 7 and 9 kb, assuming temperatures in the above range.

Using the Hb-breakdown curves of Wells (1979), the partial pressure of water in mafic lithologies can be derived from P-T estimates. This implies that P_{H_2O} = 0.2-0.4 P_{LOAD} (8.4; Fig. 12). With a knowledge of P, T and X_{H_2O}, we can examine the feasibility of melting.

Most experimental studies of granitic systems have been carried out under H_2O-saturated conditions (i.e. P_{H_2O} =

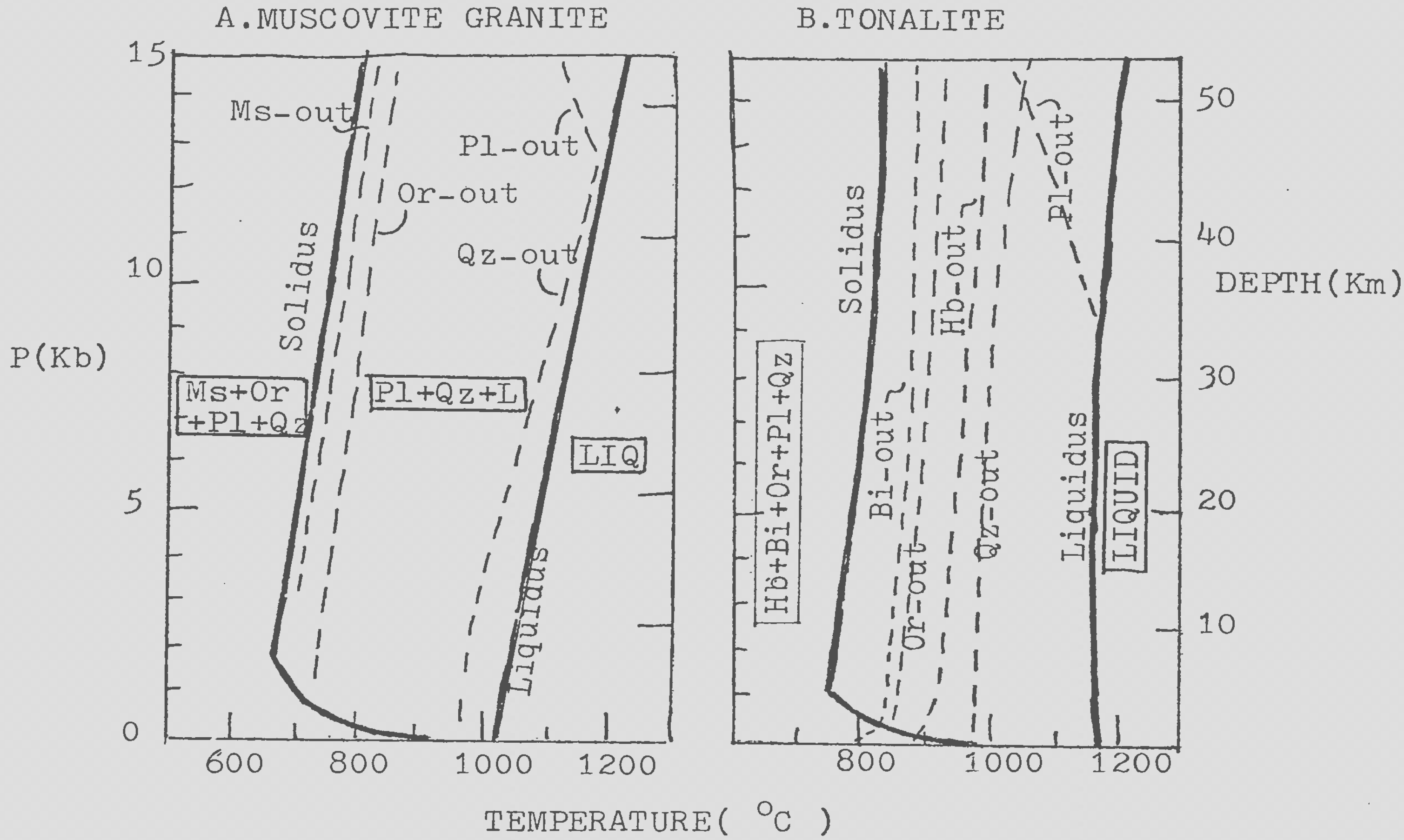


Figure 17 . Melting relationships in H_2O undersat--urated Muscovite granite and tonalite (after Wyllie, 1976) . The amount of H_2O present is just sufficient to hydrate the rocks , forming muscovite , biotite and hornblende . The tonalite can be regarded as analogous to the Uivak gneisses . The diagrams are largely schematic .

P_{LOAD}) and are thus not strictly applicable to natural rocks (Brown, 1970; Brown and Fyfe, 1970; Wyllie, 1977). Some results are available for H_2O-undersaturated conditions analogous to most natural rocks; these are reviewed by Wyllie (1977) and shown in Fig. 17. It is evident that melting in rocks of tonalitic composition (c.f. the Uivak I gneisses) would only commence at temperatures in excess of 800°C, and plagioclase would remain as a residual phase at temperatures as high as 1000°C. In rocks of granitic composition (c.f. Uivak II gneisses and pegmatite layers in Uivak I gneisses), melting would commence at c. 700°C. Under H_2O-saturated conditions (Fig. 18), rocks of either composition would be extensively molten at temperatures of 750-850°C.

The above evidence suggests that the temperatures indicated by geothermometry are insufficient for significant melting of the Uivak I suite under H_2O-undersaturated conditions. This clearly contradicts compelling evidence from field relations and petrology which indicate extensive melting. This inconsistency can be explained in two ways. Firstly, the quartzofeldspathic rocks may have had a higher initial water content than the mafic gneisses and pelitic gneiss from which P-T-X estimates were obtained. This is considered unlikely because of the protracted early metamorphic history of the Uivak I gneisses (8.2) which would have involved substantial dehydration. A second, and much more likely explanation is that water (and other volatiles)

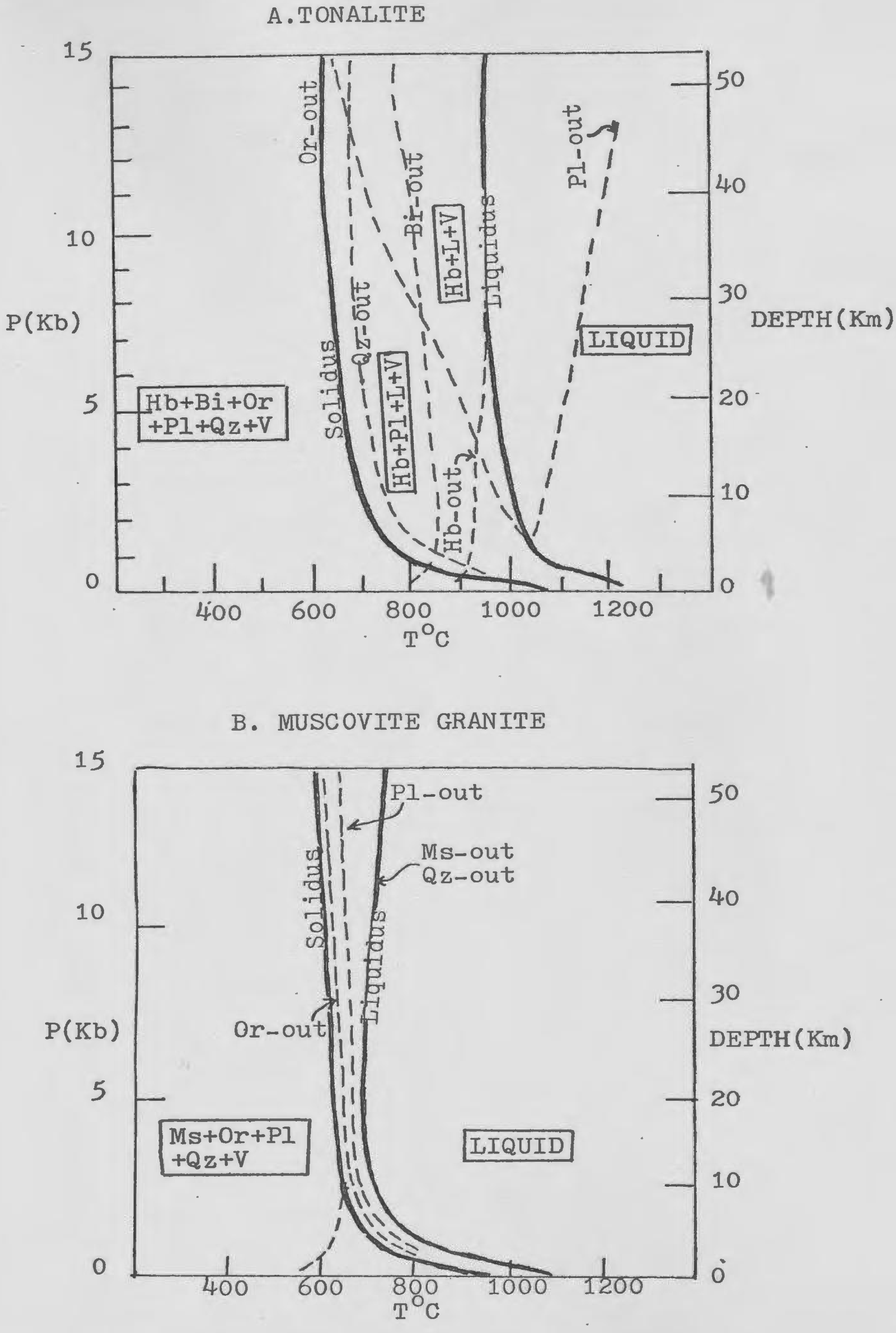


Figure 18 . H_2O Saturated melting in a muscovite granite and a tonalite (after Wyllie,1977)

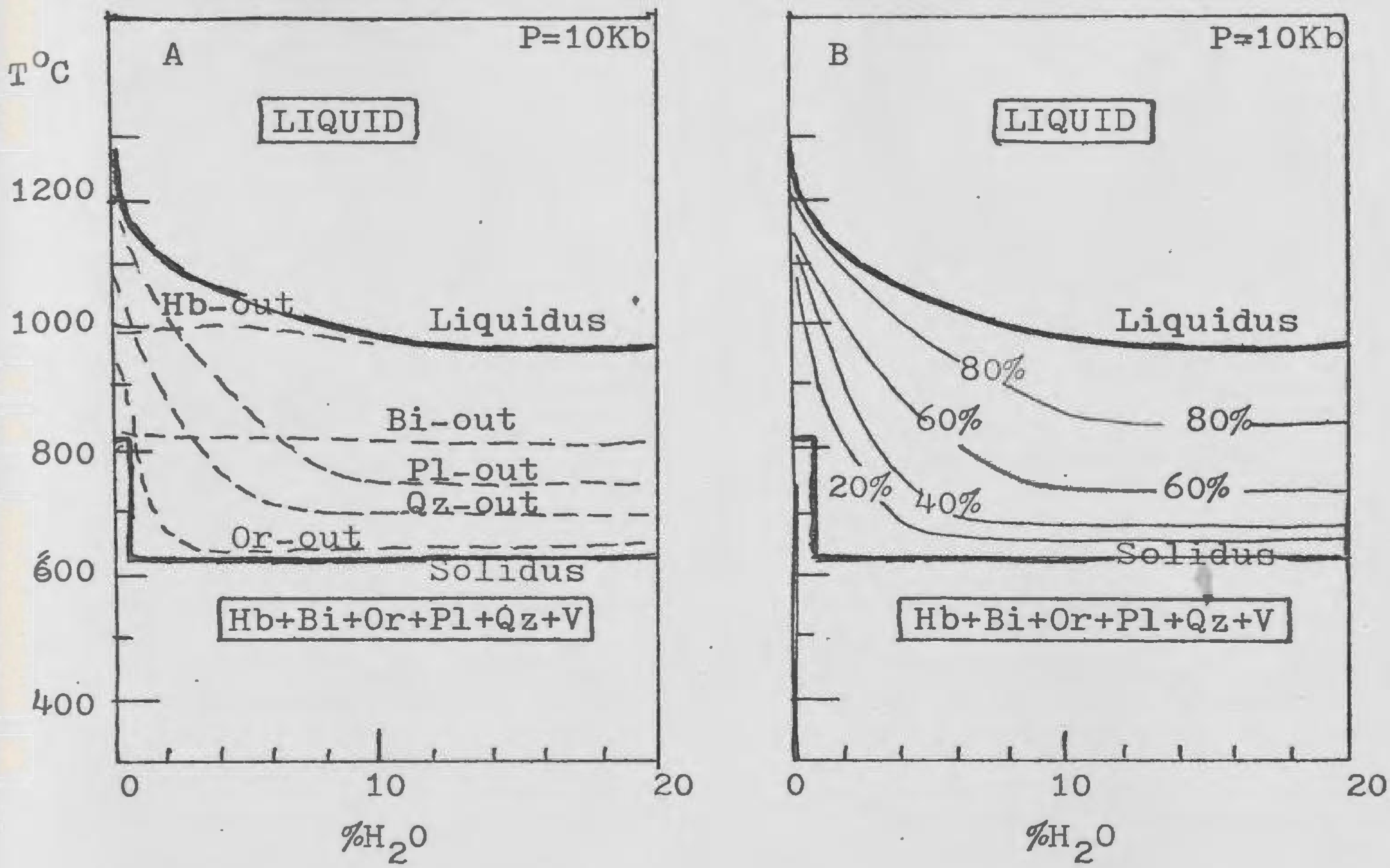


Figure 19 . Schematic diagrams illustrating the effects of H_2O upon phase relationships and melting intervals in a tonalite at 10 Kb(after Wyllie,1976) . Percentages in diagram B indicate the proportions of liquid within the melting interval.

were introduced to the quartzofeldspathic gneisses from elsewhere.

(ii) A Model for Reworking:

Clear evidence of solidus depression caused by addition of H_2O is present in the form of the Kiyuktok pegmatites, which commonly display a border zone or "halo" in which in situ melting takes place. In view of the small size of the pegmatites and the hot nature of their country rocks, this feature is unlikely to be related to local temperature increases caused by pegmatite emplacement. It is much more probable that it reflects the influx of H_2O to Uivak gneisses which were already at temperatures in excess of the H_2O-saturated solidus (c. 650^{o}C). The Kiyuktok pegmatites thus appear to have acted as a transport medium for water which was concentrated at the present level of exposure. The ternary minimum composition and petrology of these pegmatites suggests that they were derived by partial melting of Uivak gneisses and Upernavik metasediments, presumably in a zone subjacent to the present level of exposure. Fig. 20 is a schematic flow-chart which illustrates a proposed model for the formation of the Kiyuktok gneisses.

It is suggested that Uivak gneisses and Upernavik metasediments at deep crustal levels (A) underwent extensive melting and dehydration under granulite facies conditions where temperatures exceeded 900-950^{o}C. Since the calculated temperature estimates (8.3) suggest a geothermal gradient of

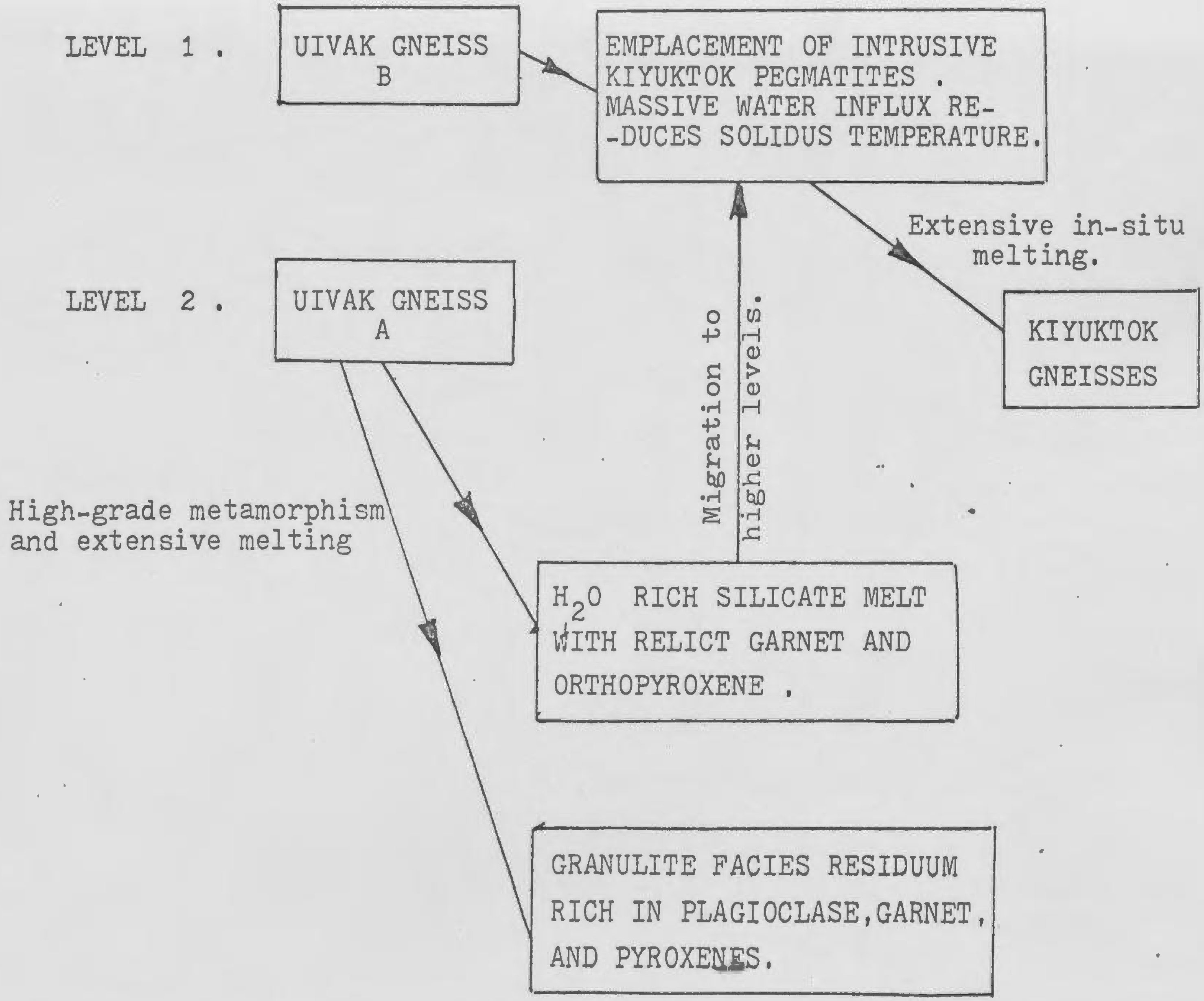
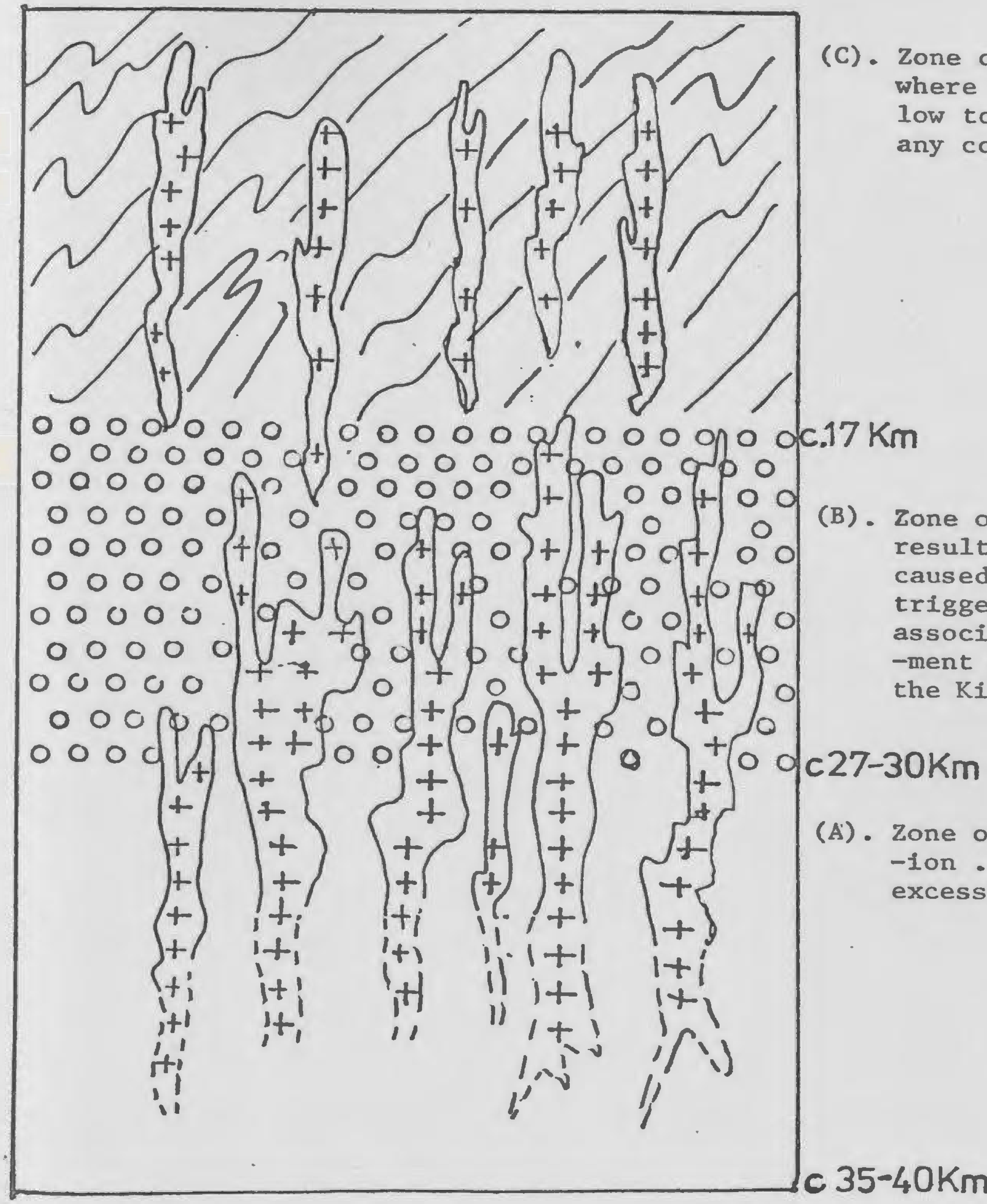


Figure 20 . A model for the formation of the Kiyuktok gneisses (see text for explanation and discussion)

c. 35-40^{o}C/km, this temperature regime would exist approximately 5 km below the present level of exposure. These melts would quickly coalesce and migrate to higher levels, carrying with them water released by dehydration and residual phases such as plagioclase, garnet and orthopyroxene.

At higher levels in the complex (B), melting was restricted to local zones of slightly higher water content, until the Kiyuktok pegmatites penetrated to this level and introduced H_2O. As a result, solidus depression was effectively instantaneous (see Fig. 19) and rapid partial melting took place in the Uivak gneisses. Any orthopyroxene which had formed in the Uivak gneisses prior to solidus depression was rapidly retrogressed to aggregates of biotite-quartz symplectites, which are now preserved as "clots" within the Kiyuktok gneisses.

The Kiyuktok gneisses are thus regarded as mixtures of various proportions of relict Uivak material (mostly plagioclase) and minimum melt, which was derived both _in situ_ and from an external source now represented by the Kiyuktok pegmatites. Kiyuktok gneisses containing larger amounts of externally derived pegmatites display a more "granitic" composition than these formed mostly by _in situ_ processes, which do not depart significantly from the Uivak I gneisses in composition. This type of interpretation is also supported by variations in isotope geochemistry (Collerson _et al._, 1980).



(C). Zone of minimal reworking where temperatures were too low to allow melting under any conditions .

(B). Zone of extensive reworking resulting from rapid melting caused by solidus depression triggered by water fluxing associated with the emplace--ment and crystallisation of the Kiyuktok pegmatites .

(A). Zone of melting and dehydrat--ion . Temperatures in excess of 900-1000 ^{o}C .

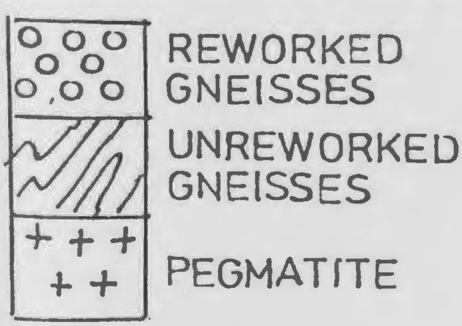


Figure 21 . Vertical zonation of the crust during the reworking of the Uivak gneisses .

Reworking by the volatile-concentration model proposed in Fig. 20 would be constrained to a zone whose upper limit is defined approximately by the intersection of the geotherm with the H_2O-saturated solidus at c. 640°C. We can thus envisage a vertical zonation of the crust into a "melting zone", a "reworking zone" and a "preserved" zone (Fig. 21). For a geothermal gradient of c. 35°C/km, the reworked zone would extend from about 17 km below surface (= 640°C/5 kb) to depths in excess of 27-30 km.

10.3.2. The Formation of Late Archean Intrusive Rocks

Although Late Archean orthogneisses derived from intrusive (s.s.) parents are of minor extent only in the Saglek area, they are important southwest of Hebron and at Nachvak Fiord. In the Saglek area, they are represented by numerous thin sheets and dykes of foliated tonalite and granodiorite (3.4, 4.4).

In the Hebron and Nachvak areas they form discrete units up to 1 km thick of granodioritic to granitic composition which are known as the Ikarut and Kammarsuit gneisses respectively (Collerson et al., 1980). Lithological and geochemical affinities between the intrusive rocks have led to the supposition that they are part of a single cogenetic suite, and the tonalite-granodiorite sheets of the study area are termed Ikarut gneisses elsewhere in this report.

However, one of the most important findings of isotopic studies conducted by Dr. K. D. Collerson at A.N.U. in 1978-79 was the recognition that these rocks, although of identical age, may have significantly different source regions. All three groups yield similar Rb/Sr ages in the range 2600-2800 Ma, but show different initial Sr isotope ratios. Tonalitic and granodioritic gneisses from the Saglek area show initial $^{87}Sr/^{86}Sr$ ratios of c. 0.7031, whereas the Ikarut and Kammarsuit gneisses have initial ratios of c. 0.7060 (further details in Collerson _et al._, 1980). Initial ratios of c. 7031 are consistent with derivation of the gneisses by partial melting of a short-lived basaltic source which had not departed appreciably from mantle $^{87}Sr/^{86}Sr$. This is similar to the interpretation of the lithologically and isotopically comparable Nuk gneisses of West Greenland (Moorbath, 1975; Moorbath and Pankhurst, 1976) and is consistent with petrological models for tonalite genesis (Barker and Arth, 1976; Wyllie, 1977).

However, the higher initial ratios of the Ikarut and Kammarsuit gneisses suggests derivation from a sialic source. This is quite feasible petrologically as these rocks are dominantly granodiorites and granites (s.s.). Application of the "Bulk Earth Method" of Cameron _et al._ (in prep.; explained in Collerson _et al._, 1980) suggests a maximum precursor age of c. 3,000 Ma for the Kammarsuit gneisses and c. 3,300 Ma for the Ikarut gneisses. Three models for the petrogenesis of these Late Archean intrusive rocks can thus be presented:

1. Partial melting of sialic sources of c. 3,000 Ma and c. 3,300 Ma age respectively.
2. Partial melting of a 3,600 Ma source with a low Rb/Sr ratio, (i.e. granulite facies Uivak gneisses).
3. Some degree of mixing between a high Rb/Sr magma such as the Kiyuktok gneisses and a relatively juvenile source material perhaps represented by the tonalite-granodiorite sheets of the Saglek area.

These models will be evaluated in the next section.

10.4. A MODEL FOR LATE ARCHEAN INFRACRUSTAL MAGMATISM

Whilst the Kiyuktok gneisses are clearly explicable in terms of reworked 3,600 Ma old sialic crust, temporally equivalent gneisses of intrusive (s.s.) origin are more difficult to interpret. It, however, is beyond discussion that the Ikarut and Kammarsuit gneisses represent melts of sialic source rocks. What is debatable is whether they represent derivatives of 3,600 Ma old crust or derivatives of younger (3,300-3,000 Ma) sialic rocks. The most important observation in this context is that sialic crust of 3,300-3,000 Ma age has not yet been recognized in Northern Labrador, although some members of the Nuk suite may be as old as this (Moorbath and Pankhurst, 1976). I therefore prefer model 3

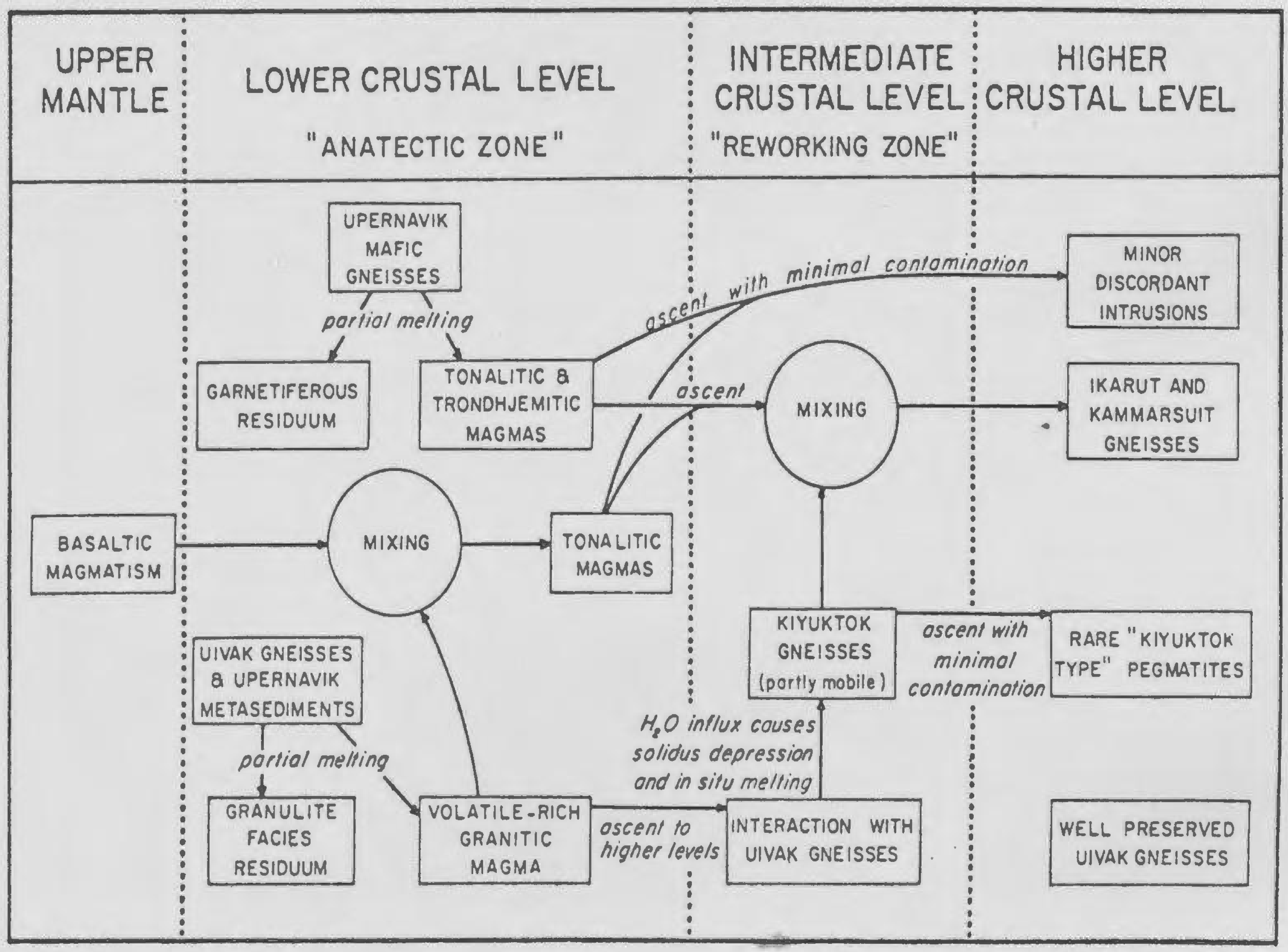


Figure 22 . The Possible Complexity of Magmatic Processes at the time of Reworking . Rocks at the present level of exposure are the results of interaction and hybridization between magmas of differing origins .

of the previous section, i.e. mixing between juvenile trondhjemite-tonalite magmas and enriched crustal melts. This leads to a model for Late Archean infracrustal magmatism which is illustrated in Fig. 22.

In the "melting zone" of the lower crust, three principal rock types occur: (1) Uivak gneisses, (2) Upernavik mafic gneisses, and (3) Upernavik metasediments. When heat is applied to this zone of the crust (the ultimate sources of this heat will be discussed below), these rocks begin to melt.

Although "granitic" minimum melts can be produced in the initial stages of basalt melting (Helz, 1976), they are severely limited in volume by the lack of normative Or in such rocks. Most of the crustal melts produced during the initial stages of this thermal event will be derived from the water-rich Upernavik metasediments and the Uivak gneisses. Dehydration and melting of these lithologies leads to the generation of the Kiyuktok pegmatites which migrate to a higher level and cause solidus depression in the Uivak gneisses (see 10.3.1.) in the "reworking zone".

With further input of heat, melting of Upernavik mafic gneisses becomes more extensive and melts of tonalitic-trondhjemite type are produced (c.f. Barker and Arth, 1976; Wyllie, 1977). Since these are derived almost exclusively from a Upernavik source, they represent "Juvenile" magmas in the sense of Moorbath (1975). However, to reach the levels presently exposed, these magmas must pass through the "reworking" zone where anatectic melting of the Uivak gneisses is prevalent.

Under such circumstances, I find it hard to believe that mixing of "juvenile", and "crustal" magmas would not occur and I suggest that the present geochemical and isotopic characteristics of the Ikarut and Kammarsuit gneisses are a result of this mixing process. Similar views are expressed by Collerson et al. (1980) and have also been suggested for modern calc-alkaline plutonic and volcanic associations (Eichelberger, 1975; Anderson, 1976; Presnall and Bateman, 1973).

The main problem which remains is the ultimate source of the heat required for magma genesis in the "melting" zone of the crust. There are three possible models:

(1) Depression of the base of the crust in response to crustal thickening of some sort.

(2) Emplacement of mafic magmas derived from subjacent mantle.

(3) Some combination of the above.

Process (1) could result from early thickening by thrusting and recumbent folding associated with intercalation of the Upernavik suite and the Uivak gneisses. However, process (2), which would probably also incorporate some resultant crustal thickening, is a much more effective means of transmitting heat to the lower crust. Crustal melting during the emplacement of basaltic magmas is quite feasible (Patchett, 1980).

A model involving basaltic magmatism is particularly attractive for a number of reasons. Firstly, it provides an additional source of "juvenile" mafic material for the production of tonalite-trondhjemite magmas. In areas where "juvenile"-type Late Archean gneisses are abundant (e.g. West Greenland), this process may be very important.

In this context, thermal models for magmatic crustal thickening (Wells, 1979; 1980) are of special interest. Models which assume over-accretion (i.e. emplacement of successive sheets at the same level, and displacement of earlier sheets to lower levels) imply a fluctuating temperature profile and progressive displacement of earlier sheets to deeper and therefore hotter levels. We can thus envisage a situation where juvenile mafic material is subsequently partially melted by a later magma pulse. This would provide a source for large quantities of juvenile tonalitic-trondhjemitic gneisses such as the Nuk gneisses.

In such a regime, hybridization of magmas via the concept in Fig. 22 would be heavily biased towards the "juvenile" end of the spectrum, making recognition of crustal melts difficult. In areas such as Northern Labrador, where crustal melts are better preserved, the mantle derived contribution may have been significantly less.

10.5. CONCLUDING REMARKS

This thesis, and the results of Collerson et al. (1980), have demonstrated a number of points:

(1) Anatectic reworking of sialic crust upon a regional scale occurred in Northern Labrador and was a direct consequence of volatile migration and concentration and resultant solidus depression.

(2) Late Archean gneisses of intrusive (s.s.) origin are of mixed character and can be explained in terms of mixing of "juvenile" magma and crustal melts of Kiyuktok type.

(3) Late Archean thermal events are probably best explained by a combination of crustal thickening via tectonism and basaltic magmatism at the base of the crust.

Topics worthy of further investigation are:

(1) The possible importance of reworking in Early Archean crustal development, when geothermal gradients were substantially greater (e.g. Fyfe, 1973) and isotopic exchange with the mantle more likely (c.f. Collerson and Fryer, 1979).

(2) The importance of magma mixing via the scheme in Fig. 22 in the petrogenesis of modern calc-alkaline suites, which have often been proposed as analogous of Archean grey gneiss complexes (Windley and Smith, 1976; Tarney, 1976; Burke et al., 1976).

(3) The geochemical changes which may accompany

reworking as a result of volatile migration (c.f. Collerson and Fryer, 1978) involved in solidus depression and in situ anatexis.

(4) The possible importance of early crustal thickening as a causative mechanism for crustal subsidence and melting.

(5) The thermal effects of basaltic magmatism in the base of the crust (c.f. Patchett, 1980; Wells, 1980).

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TABLE 4: Typical mineral analyses from the Kiyuktok Gneisses.

	AK-78-4 OPX	KC-78-208A OPX	AK-78-4B OPX	AK-78-104 GREEN BI	KC-78-20AJ GREEN BI	AK-78-104 GT	KC-78-208J GT
SiO_2	52.37	53.49	54.41	35.62	35.12	28.10	38.54
TiO_2	00.04	00.07	--	00.60	00.97	00.02	00.03
Al_2O_3	00.44	01.45	00.86	21.39	19.22	21.84	22.02
Cr_2O_3	--	--	00.03	--	--	--	--
Fe_2O_3	--	--	--	--	--	--	--
FeO	30.35	26.89	28.84	21.07	26.58	31.47	34.03
MnO	20.61	00.58	00.71	00.09	00.17	01.56	01.57
MgO	15.05	17.70	14.43	09.47	06.03	04.98	03.15
CaO	00.57	00.47	00.73	00.02	00.01	02.15	01.78
Na_2O	00.04	--	00.03	00.05	00.02	--	--
K_2O	--	--	00.09	09.06	09.21	--	--
TOTAL	99.48	98.76	100.17	96.58	97.33	100.13	101.12
CATION PROP							
Si	2.03	2.01	2.06			6.10	6.10
Al	0.09	0.09	0.17			4.24	4.09
Ti	--	--	--			--	--
Cr	--	--	--			--	--
Fe (3)	--	--	--			--	--
Fe (2)	0.98	0.85	0.95			4.076	4.48
Mg	0.87	0.99	0.81			1.1	0.739
Mn	0.02	0.02	0.02			0.20	0.21
Ni	--	--	--			--	--
Ca	0.02	0.02	0.02			1.109	--
Na	--	--	--			--	--
K	--	--	--			--	--
TOTAL	3.957	3.954	3.914			15.880	15.886

*Analysis of relict minerals (i.e. Opx and Gt) is hampered by varying degrees of alteration.

TABLE 5: Major element analyses and partial C.I.P.W. normative compositions of representative Kiyuktok Gneisses.

SAMPLE NO. Wt %	1	2	3	4	5	6	7	8	9
SiO_2	71.30	73.40	70.40	71.30	70.00	72.50	71.20	70.9	71.2
TiO_2	0.26	0.17	0.30	0.18	0.22	0.15	0.24	0.26	0.18
Al_2O_3	14.90	14.44	15.7	15.2	15.5	13.6	15.70	15.60	15.0
Fe_2O_3	0.55	0.21	0.58	0.12	0.39	0.14	0.29	0.21	0.30
FeO	1.40	0.86	2.15	1.26	1.68	1.21	1.54	1.82	1.37
MnO	0.03	00.01	00.05	0.02	0.04	00.02	0.03	0.03	0.03
MgO	0.73	0.27	1.02	0.61	0.70	0.30	0.64	0.68	0.74
CaO	2.35	1.79	2.70	2.31	2.78	1.37	2.04	2.72	2.40
Na_2O	4.59	3.96	4.52	4.94	4.80	3.51	4.35	5.03	4.80
K_2O	2.73	3.99	2.14	2.40	1.78	4.66	3.21	1.58	2.31
P_2O_5	0.05	00.02	0.05	0.06	0.10	0.04	0.12	0.13	0.12
L.O.I.	0.62	0.55	0.72	0.05	1.25	0.97	1.03	0.40	0.40
TOTAL	99.41	99.64	100.33	99.03	99.25	99.55	100.39	99.36	98.88
CIPW NORMS									
Q	27.5	30.62	27.33	26.97	27.72	30.67	48.79	27.80	27.73
Or	16.32	23.80	12.70	14.41	10.75	28.24	21.26	9.45	13.88
Ab	39.30	33.83	38.42	42.46	41.49	30.46	12.83	43.07	41.31
An	11.80	8.96	13.45	11.64	14.09	6.97	--	13.65	12.11

TABLE 5 (Continued)

SAMPLE NO. Wt. %	10	11	12	13	14	15	16	17	18
SiO_2	71.40	72.50	71.70	70.20	70.50	74.20	72.70	74.0	74.90
TiO_2	0.28	0.17	0.15	0.30	0.17	0.02	0.13	0.04	0.07
Al_2O_3	15.0	14.80	15.3	14.8	15.10	14.00	15.10	14.50	13.6
Fe_2O_3	0.10	0.37	0.37	0.39	0.12	0.45	0.78	0.14	0.30
FeO	1.76	1.19	0.75	1.54	0.70	0.77	1.30	0.53	0.31
MnO	0.03	0.03	0.01	0.02	0.00	0.02	0.02	0.02	0.02
MgO	0.81	0.46	0.41	0.93	0.32	0.22	0.69	0.18	0.14
CaO	2.95	2.49	2.86	2.25	2.37	1.02	3.89	1.56	1.31
Na_2O	3.99	4.70	5.15	3.97	4.64	3.52	4.29	4.00	3.10
K_2O	2.80	2.04	1.49	3.50	3.00	5.04	0.73	4.36	5.46
P_2O_5	0.06	0.04	0.06	0.15	0.02	0.05	0.01	0.05	0.05
L.O.I.	0.70	0.65	0.51	0.81	0.59	0.21	0.66	0.32	0.64
TOTAL	99.99	99.44	98.76	98.86	99.53	99.52	99.31	97.70	99.90
CIPW NORMS									
Q	28.95	30.96	29.45	27.14	26.94	31.68	35.00	30.26	33.11
Or	16.69	12.21	8.97	21.13	18.29	30.01	4.33	25.94	32.52
Ab	34.06	40.27	44.38	34.31	40.51	30.01	36.44	34.08	26.44
An	14.77	12.51	14.48	11.40	11.88	5.10	19.37	7.79	6.55

KEY FOR TABLE 5:

1 --	AK-78-K3	Kiyuktok gneiss with Uivak remnants, Kiyuktok Cove.
2 --	AK-78-56	Kiyuktok gneiss with Uivak remnants, Heart Lake.
3 --	AK-78-104	Kiyuktok gneiss with prominent "ghost" layering and scattered Uivak remnants. Near Bob's Pond.
4 --	KC-75-208I	Kiyuktok gneisses with Uivak remnants, Kiyuktok Cove.
5 --	KC-75-208O	
6 --	KC-78-634B	Uivak II gneiss with concordant Kiyuktok pegmatites, Fire Cove.
7 --	KC-75-208M	Kiyuktok gneisses with remnants, Kiyuktok Cove.
8 --	KC-75-208K	
9 --	KC-76-345D	Kiyuktok gneiss with Uivak remnants, Shuldham Island.
10 --	AK-78-4	Nebulitic Kiyuktok gneiss, Heart Lake.
11 --	KC-76-411B	Nebulitic Kiyuktok gneisses containing Saglek dyke remnants, Ramah Bay.
12 --	KC-76-412B	
13 --	KC-76-412F	
14 --	AK-77-11A	Intrusive Kiyuktok pegmatite, Torr Bay.
15 --	KC-75-208L	"Pegmatitic" Kiyuktok gneiss. Origin uncertain. Kiyuktok Cove.
16 --	KC-78-208A	Orthopyroxene-bearing pegmatite, Kiyuktok Cove.
17 --	AK-78-K33	Intrusive Kiyuktok pegmatites, Kiyuktok Cove.
18 --	AK-78-K34	

Table 6: Representative mineral analyses from Upernavik supracrustal rocks.

Sample No.	AK-78-51A		AK-78-115B		AK-78-262		AK-77-53	
Mineral Wt %	CPX	OPX	CPX	OPX	CPX	OPX	CPX	GT
SiO_2	51.37	52.76	53.00	52.75	53.49	52.75	51.77	38.06
TiO_2	0.13	0.03	0.14	0.046	0.06	0.04	0.115	0.03
Al_2O_3	2.71	1.38	1.87	1.33	00.73	0.38	1.125	21.49
Cr_2O_3	0.03	0.02	0.19	0.12	--	--	0.04	0.16
FeO	6.21	20.39	6.05	21.79	8.93	27.10	12.07	29.07
MnO	0.13	0.35	0.13	0.34	00.11	0.32	0.12	1.00
MgO	14.06	24.12	14.96	23.79	14.01	20.10	11.94	3.75
CaO	22.8	0.32	23.68	0.37	22.55	0.45	22.59	7.49
Na_2O	0.35	0.01	0.32	--	00.29	0.04	0.26	0.01
K_2O	--	--	--	--	--	--	--	--
TOTAL	97.80	99.38	100.33	100.56	100.23	101.23	100.03	101.07
CATION PROP								
Si	1.938	1.954	1.947	1.952	1.989	1.978	1.953	5.964
Al	0.120	0.060	0.081	0.058	0.032	0.017	0.051	3.971
Ti	0.004	0.007	0.004	0.001	0.002	0.001	0.003	0.004
Cr	0.001	0.001	0.006	0.003	--	--	0.001	0.020
Fe (3)	0.021	0.0	0.035	0.0	0.007	0.028	0.054	0.0
Fe (2)	0.175	0.632	0.151	0.654	0.270	0.822	0.334	3.810
Mg	0.791	1.331	0.819	1.325	0.777	1.123	0.659	0.876
Mn	0.004	0.011	0.004	0.010	0.003	0.010	0.004	0.133
Ni	--	--	--	--	--	--	--	--
Ca	0.922	0.013	0.932	0.013	0.899	0.018	0.923	1.258
Na	0.025	0.0	0.022	0.0	0.021	0.003	0.018	0.003
K	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	4.000	4.009	4.000	4.016	4.000	4.000	4.000	16.038

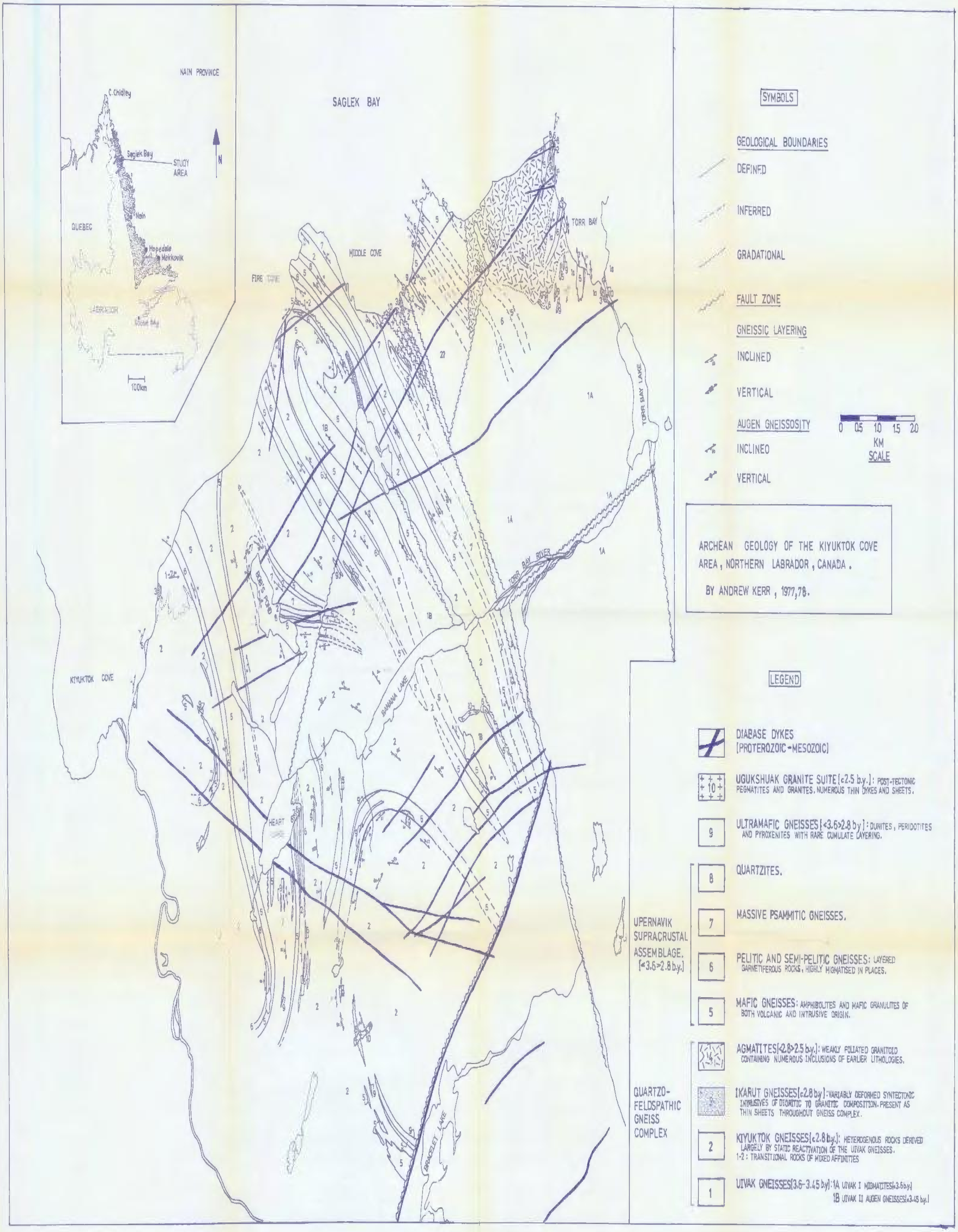
Table 6 (Continued)

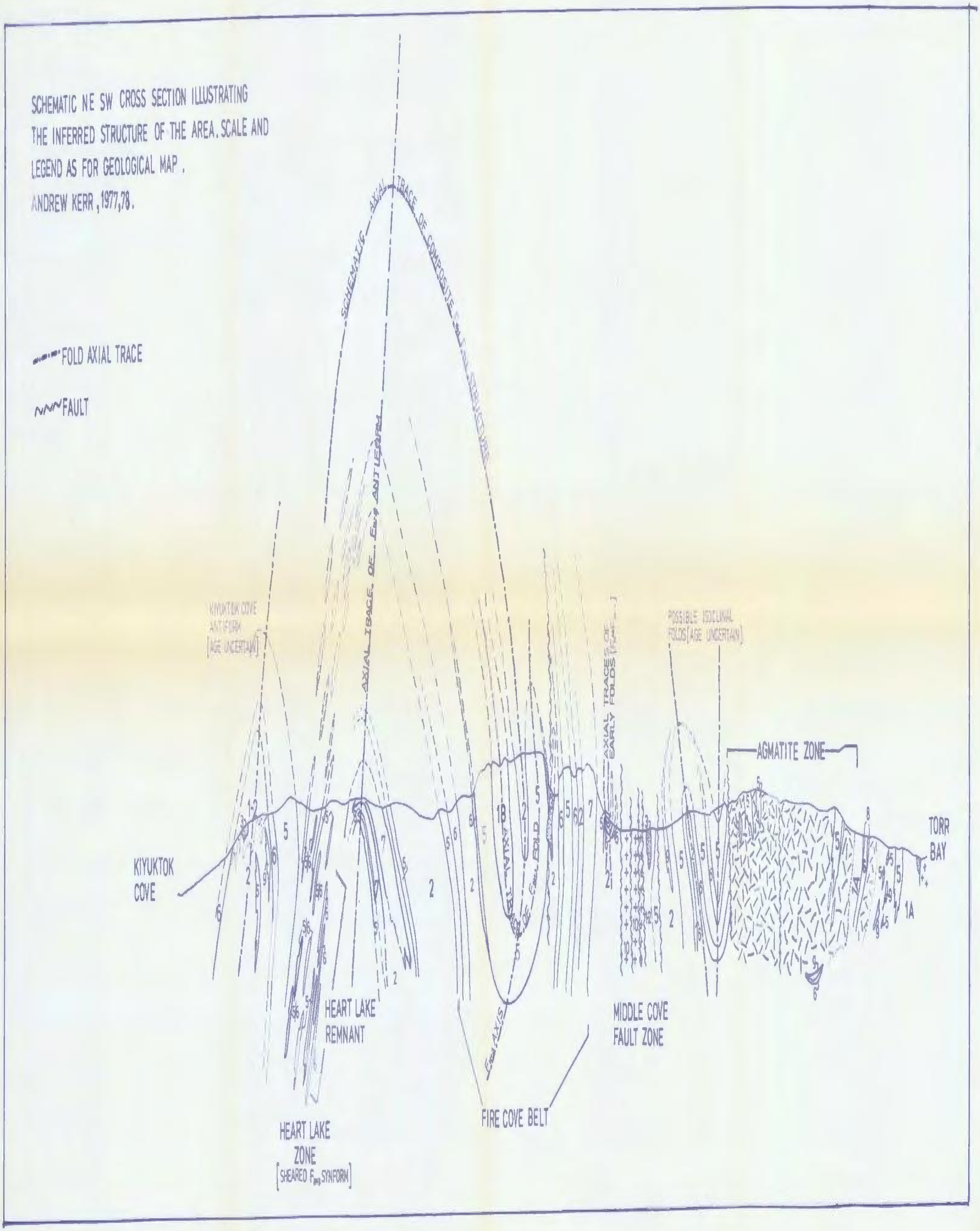
Sample No.	AK-78-270B			AK-78-271		AK-78-116		
Mineral Wt %	CPX	OPX	GT	CPX	GT	GT	CORD	BI
SiO_2	52.27	52.96	39.43	50.14	38.80	40.76	51.13	36.56
TiO_2	00.20	0.06	0.03	0.13	0.05	0.016	0.0	3.16
Al_2O_3	1.57	1.14	22.11	1.40	21.75	23.53	34.00	16.79
Cr_2O_3	--	--	--	--	--	0.216	--	0.43
FeO	11.70	27.45	26.81	14.86	29.50	21.83	2.53	9.97
MnO	0.18	0.61	1.54	0.88	00.88	0.173	--	--
MgO	12.60	18.04	5.23	10.88	3.61	14.27	11.68	17.11
CaO	22.24	0.75	6.59	21.42	7.07	0.58	--	--
Na_2O	0.36	--	--	0.35	--	0.026	0.04	0.09
K_2O	00.00	--	--	--	--	--	--	8.59
TOTAL	101.14	100.99	101.75	99.29	101.67	101.4	99.38	92.70
CATION PROP								
Si	1.945	1.947	6.042	1.971	6.026	5.974	1.686	--
Al	0.068	0.041	4.079	0.053	4.036	4.066	1.322	--
Ti	0.006	0.002	0.006	0.003	0.006	0.002	--	--
Cr	--	--	--	--	--	--	--	--
Fe (3)	0.057	0.064	--	0.022	--	--	--	--
Fe (2)	0.307	0.896	3.436	0.424	3.832	2.676	0.07	--
Mg	0.699	1.015	0.195	0.646	0.836	3.117	0.574	--
Mn	0.006	0.013	0.200	0.002	0.116	0.021	--	--
Ni	--	--	--	--	--	--	--	--
Ca	0.887	0.019	1.082	0.857	1.177	0.091	--	--
Na	0.026	0.002	--	0.022	--	0.009	0.003	--
K	--	--	--	--	--	--	--	--
TOTAL	4.000	4.000	15.955	4.000	15.976	15.982	3.654	--

Table 6 (Continued):

KEY:

AK-78-51A	Plagioclase-rich mafic granulite. Near Banana Lake.
AK-78-115B	Mafic Granulite. Near Heart Lake.
AK-78-262	Psammitic Metasediment. Middle Cove.
AK-77-53	Mafic Granulite. Middle Cove.
AK-78-270B	Mafic Granulite. 1 km south of Middle Cove.
AK-78-271	Cpx-Gt-Qz rock. Probably a metasediment. 1 km south of Middle Cove.
AK-78-116	Semi-pelite. Near Heart Lake.


NAIN PROVINCE
C. Chidley
Saglek Bay
STUDY AREA
N
QUEBEC
Nain
Hopedale
Makkovik
LABRADOR
100km
SAGLEK BAY
MIDDLE COVE
TORR BAY
TORR BAY LAKE
TORR BAY RIVER
KIYUKTOK COVE
BANANA LAKE
HEART
SYMBOLS
GEOLOGICAL BOUNDARIES
DEFINED
INFERRED
GRADATIONAL
FAULT ZONE
GNEISSIC LAYERING
INCLINED
VERTICAL
AUGEN GNEISSOSITY
INCLINED
VERTICAL
0 0.5 1.0 1.5 2.0
KM
SCALE
ARCHEAN GEOLOGY OF THE KIYUKTOK COVE AREA, NORTHERN LABRADOR, CANADA.
BY ANDREW KERR, 1977,78.
LEGEND
DIABASE DYKES [PROTEROZOIC-MESOZOIC]
10 UGUKSHUAK GRANITE SUITE [<2.5 b.y.]: POST-TECTONIC PEGMATITES AND GRANITES. NUMEROUS THIN DYKES AND SHEETS.
9 ULTRAMAFIC GNEISSES [<3.6>2.8 b.y.]: DUNITES, PERIDOTITES AND PYROXENITES WITH RARE CUMULATE LAYERING.
UPERNAVIK SUPRACRUSTAL ASSEMBLAGE. [<3.6>2.8 b.y.]
8 QUARTZITES.
7 MASSIVE PSAMMITIC GNEISSES.
6 PELITIC AND SEMI-PELITIC GNEISSES: LAYERED GARNETIFEROUS ROCKS, HIGHLY MIGMATISED IN PLACES.
5 MAFIC GNEISSES: AMPHIBOLITES AND MAFIC GRANULITES OF BOTH VOLCANIC AND INTRUSIVE ORIGIN.
QUARTZO-FELDSPATHIC GNEISS COMPLEX
4 AGMATITES [<2.8>2.5 b.y.]: WEAKLY FOLIATED GRANITOID CONTAINING NUMEROUS INCLUSIONS OF EARLIER LITHOLOGIES.
IKARUT GNEISSES [<2.8 b.y.]: VARIABLY DEFORMED SYNTECTONIC INTRUSIVES OF DIORITIC TO GRANITIC COMPOSITION. PRESENT AS THIN SHEETS THROUGHOUT GNEISS COMPLEX.
2 KIYUKTOK GNEISSES [<2.8 b.y.]: HETEROGENOUS ROCKS DERIVED LARGELY BY STATIC REACTIVATION OF THE UIVAK GNEISSES.
1-2: TRANSITIONAL ROCKS OF MIXED AFFINITIES
1 UIVAK GNEISSES [3.6-3.45 b.y.]: 1A UIVAK I MIGMATITES [>3.6 b.y.]
1B UIVAK II AUGEN GNEISSES [<3.45 b.y.]


SCHEMATIC NE SW CROSS SECTION ILLUSTRATING
THE INFERRED STRUCTURE OF THE AREA. SCALE AND
LEGEND AS FOR GEOLOGICAL MAP.
ANDREW KERR, 1977,78.
FOLD AXIAL TRACE
FAULT
SCHEMATIC AXIAL TRACE OF COMPOSITE
AXIAL TRACE OF
KIYUKTOK COVE ANTIFORM [AGE UNCERTAIN]
AXIAL TRACES OF EARLY FOLDS
POSSIBLE ISOCLINAL FOLDS [AGE UNCERTAIN]
AGMATITE ZONE
KIYUKTOK COVE
TORR BAY
HEART LAKE REMNANT
MIDDLE COVE FAULT ZONE
FIRE COVE BELT
HEART LAKE ZONE
[SHEARED SYNFORM]