

METAMORPHISM ACROSS THE ENGLISH RIVER
GNEISSIC BELT, ALONG THE RED LAKE ROAD

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Abstract

The English River gneissic belt of northwestern Ontario contains metamorphic rocks of higher grade metamorphism than the adjacent greenstone belts. Mineral assemblages of forty-two rocks, along the Red Lake road traverse of the gneissic belt, were determined by thin section study. Recrystallization is complex; commonly a well-defined equilibrium assemblage, commonly minor retrograde alteration, rarely two prograde recrystallizations. The composition of plagioclases for various assemblages was determined, all have An > 28 per cent. Major element analyses of amphibolite and metasedimentary rocks was a control on comparison of plagioclase compositions.

The grade of metamorphism in the southern and northern portions of the belt, along the Red Lake road traverse, is that of upper amphibolite facies, that is, andesine-epidote-amphibolite subfacies. In the central portion of the belt, along the Red Lake road traverse, the grade is hornblende-orthopyroxene-granulite subfacies, which indicates that these rocks formed under conditions of higher temperature, with P_{H_2O} much lower than confining pressure.

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CHAPTER I

Introduction

The English River gneissic belt is an east - west trending subprovince in the central portion of the Superior Province of the Canadian Shield (Wilson, 1971). Little petrographic work has been done on the English River gneisses and it is the aim of this thesis to present data on the metamorphism across the belt along the Red Lake road.

Location

The English River gneissic belt extends eastward from Lake Winnipeg to the Paleozoic sedimentary rocks of the James Bay lowlands and is approximately fifty to seventy-five miles wide (Figure 1). The extremities of the belt are covered by Paleozoic rocks and therefore its exact length is not known. The belt is between the Uchi and Wabigoon volcanic belts, to the north and south respectively. The southern boundary is marked by the surface expression of a fault along the Red Lake road, but the northern boundary zone is covered by overburden.

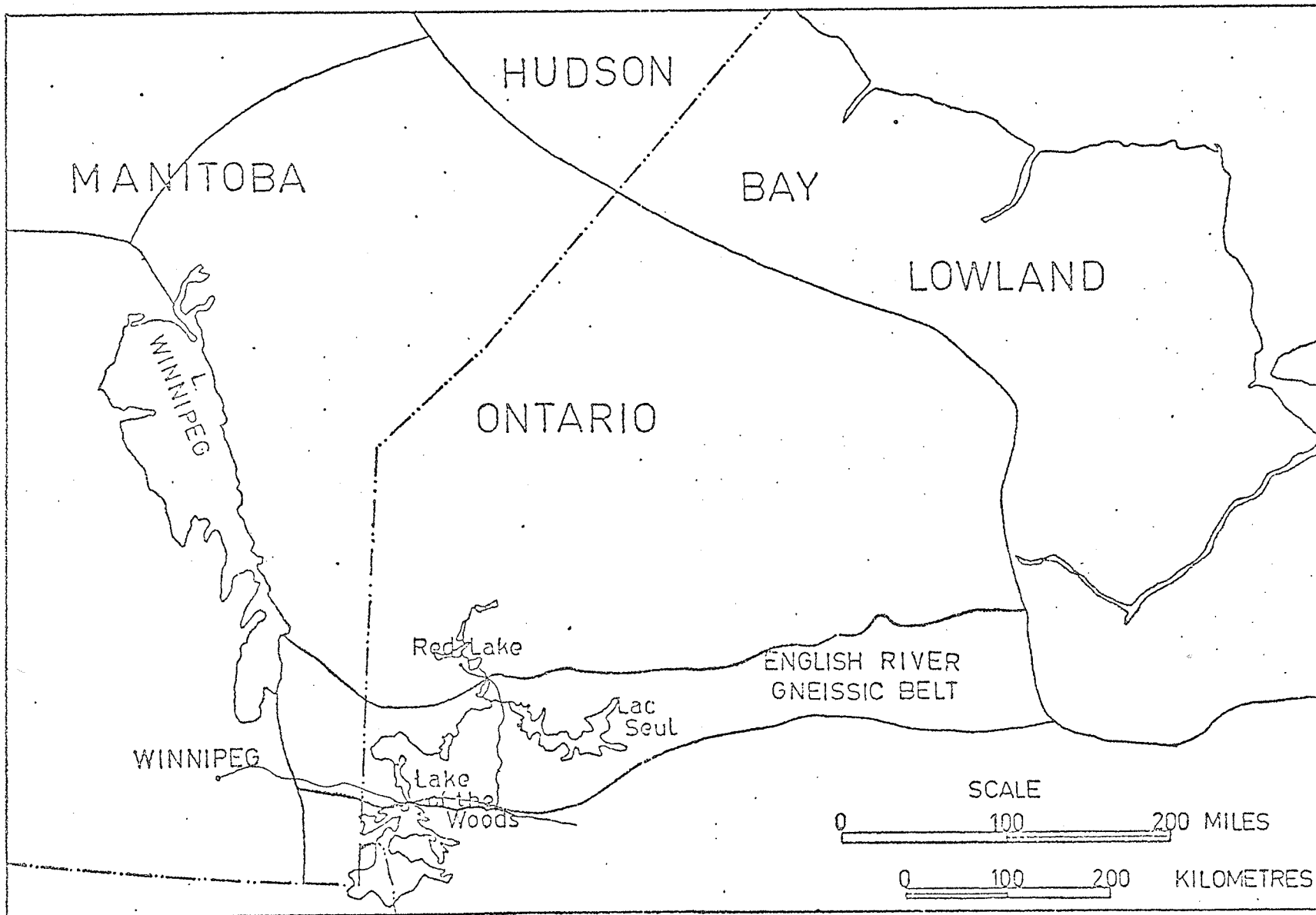


FIG.1 INDEX MAP SHOWING LOCATION OF ENGLISH RIVER GNEISSIC BELT

Previous Work

The English River gneissic belt has only been mapped in a reconnaissance manner. Work has been done in southeastern Manitoba by Wright (1932), Springer (1949), and Davies (1955, 1956).

In the Ontario portion the earliest work available is by Bruce (1924) in the upper part of the English River. Gilbert (1927) mapped in the Gammon River and Rickaby Lake schist belt while Derry (1930) did a reconnaissance mapping of the area from Minaki to Sydney Lake. Carlson (1951) mapped the Werner - Rex Lake area close to the boundary between Manitoba and Ontario. In the more eastern portion of the belt Williamson and Hudec (1958) and Hudec (1965) mapped areas north of the east part of Lac Seul. The petrography of the belt was studied by Dwibedi (1966). Wilson (1971) described the general structure of the gneissic belt, and suggested that the term block rather than belt would be more appropriate.

Seismic work has been carried out by the University of Manitoba since 1961 across the English River gneissic belt in the District of Kenora, Ontario, and the adjacent part of Manitoba, east of Lake Winnipeg (Hall and Hajnal, 1969).

Present Work and Method of Investigation

Representative samples were taken of all amphibolite and metasedimentary outcrops (Figure 2). Sample numbers are mileage values, from 0.0 miles at junction of Trans Canada Highway and Red Lake road to 65.0 miles at Ear Falls.

Emphasis was placed on the plagioclase compositions of the amphibolites and metasediments. Plagioclase compositions have been used in this work to determine variation in metamorphic grade. Those amphibolites and metasediments which contained sufficient plagioclase and were of large enough grain size to permit use of the oil immersion method were studied for anorthite content. In all, twenty-one samples were analyzed using the Revised Dispersion Method Chart of Morse (1968) for low plagioclase; three trials were carried out on each sample to check for any variation which might occur within the specimen. Lack of zoning and alteration in the plagioclase grains made this method both practical and useful for the area under study.

Twenty-five whole rock analyses were obtained, including all amphibolites and metasediments studied for

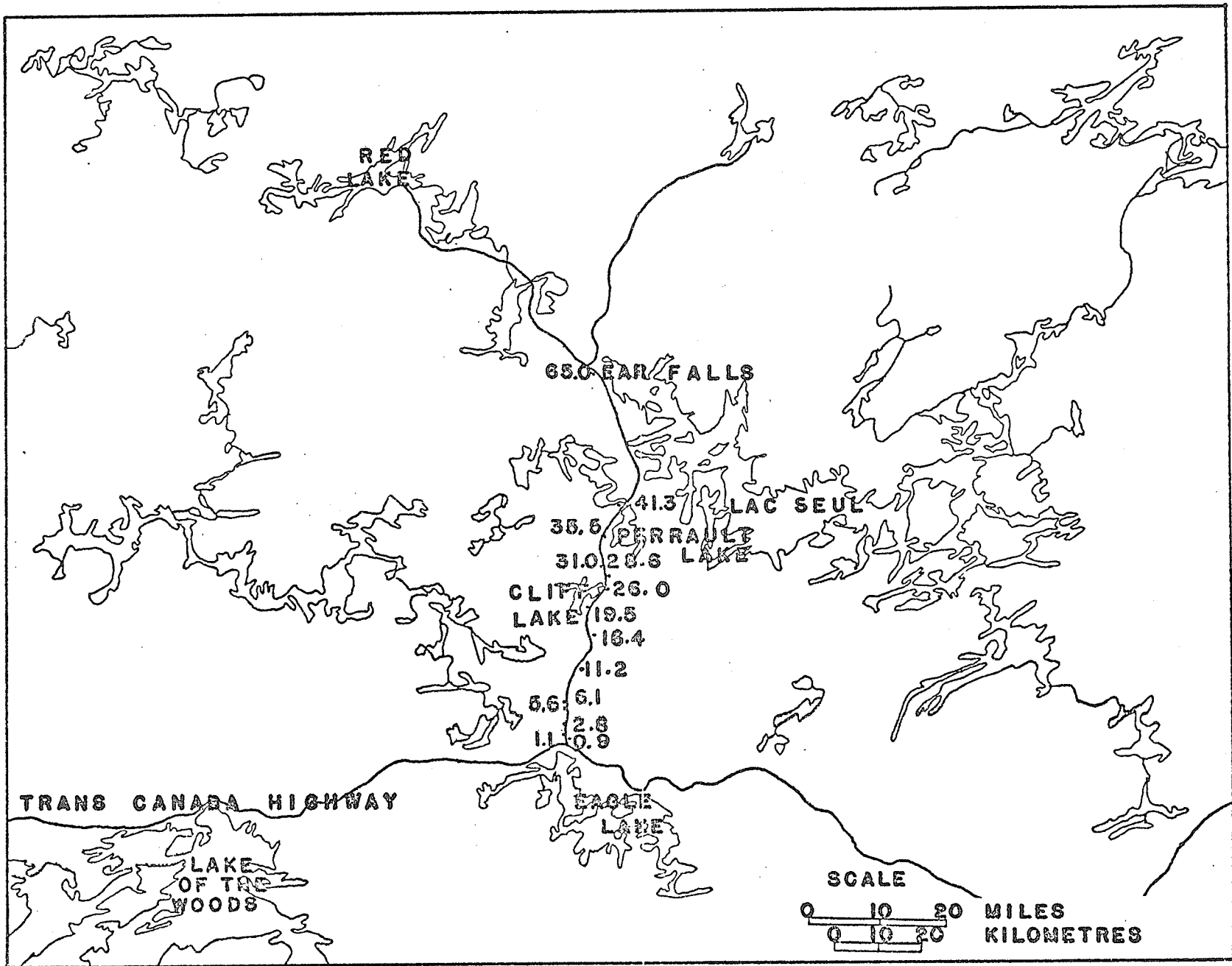


FIG. 2 SAMPLE LOCATION MAP

NUMBERS REPRESENT MILES UP THE RED LAKE ROAD

plagioclase composition. The composition of plagioclases can vary in chemically different rocks, even though they may have been metamorphosed under the same physical conditions (Chatterjee, 1961), so similar bulk composition is a condition for comparison of the anorthite content of plagioclase.

Forty-two thin sections were studied in detail to determine mineral composition, texture and mineral assemblages.

Acknowledgements

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CHAPTER II

General Geology

The rocks of the English River gneissic belt are Archean in age (Stockwell, 1970). The rocks in the belt are paragneisses, amphibolites, migmatites, granitized sediments, and granitic intrusions ranging in composition from quartz diorite to granite. The rock types are described in Chapters III, IV, and V. High grade regional metamorphism in the area has generally destroyed the primary sedimentary structures and textures. The grade of regional metamorphism within the belt is upper amphibolite facies and in places granulite facies. The greenstone belt to the south of the gneisses, near the contact with the English River belt, is also upper amphibolite facies of metamorphism. The metasediments within the belt along the Red Lake road traverse, are folded about easterly - trending axes that commonly plunge east. Chemical compositions of the metasediments indicate that they are mostly greywackes, which in turn indicates deposition in eugeosynclinal basins. Many parts of the metasedimentary sequence are migmatitic as a result of partial melting

during high grade regional metamorphism.

The belt is associated with a positive gravity anomaly which extends east of the Manitoba border for about 180 miles and lies entirely within the English River belt. This Bouguer gravity anomaly is not fully explained, although the total crust is thinner than average and sedimentary gneiss is slightly denser than granodiorite (Wilson, 1971). The thin crust, with mantle closer to the surface, may cause the gravity high.

Seismic studies by Hall and Hajnal (1969) indicate that a two layer crust exists. They described the east-west upwarp in the Mohorovicic discontinuity and a corresponding downwarp in the Intermediate discontinuity, both between latitudes 50° and 51° ; this coincides closely with the position of the English River gneissic belt. The axes of upwarp and of downwarp do not coincide exactly in plan. Hall and Hajnal (1969) suggests that, since the mass per unit area from the surface down to a reference level below the base of the crust is nearly the same everywhere in the area, the upwarp in the lower discontinuity and the downwarp in the upper discontinuity appear to be the result of processes which tended to establish isostatic equilibrium. The structure is suggestive of blocks with faults at their

margins.

The English River gneissic belt is distinguished not only by this peculiar crustal configuration. Also, in Archean time, a deep sedimentary trough developed that became the focus of a strongly heated zone which resulted in deformation, metamorphism and anatexis (Wilson, 1971).

CHAPTER III

Metasedimentary Rocks

Petrography

There are four types of metasedimentary rocks in the area under study:

1. biotite-plagioclase-schists
2. biotite-plagioclase-gneisses
3. granulites
4. migmatites

Further west, where less altered types of sedimentary rock are found, such as greywacke and arkose, the grade of metamorphism is lower (Dwibedi, 1966). This suggests that these schists, gneisses and granulites along the Red Lake road are the metamorphic equivalents of these less altered varieties. Bedding is preserved in these metamorphic rocks along the Red Lake road, injection of granitic material parallel to the bedding planes has helped to accentuate the bedding features.

The metasedimentary rocks of the greenstone belt south of the southern fault boundary of the gneissic belt, that is south of mileage 2.7, are fine grained biotite-

plagioclase-schists. The schistosity is better developed in those rocks nearer to the boundary. Relict sedimentary layering is common, and the relict texture of greywackes, coarse-grained rock fragments in a finer-grained matrix, is rare (Figure 3).

Biotite content of these schists varies between 10 - 25 per cent of the rock, plagioclase varies from 20 - 40 per cent, and quartz between 35 - 65 per cent (Table 1). Hornblende occurs only in those rocks near the fault contact, comprising between 5 - 10 per cent of the rock. No epidote occurs in the schists south of the gneissic belt. Accessory minerals are chlorite, a result of retrograde alteration of biotite, calcite, apatite, sericite, magnetite, sphene and zircon.

A well defined equilibrium assemblage of quartz + biotite + andesine + microcline occurs in these rocks. Minor retrograde alteration of biotite to chlorite occurs near the fault contact. Biotite partly altered to hornblende is present near the fault contact.

From the south edge of the gneissic belt to Ear Falls the metasediments are biotite - plagioclase - gneisses. Fine - to medium-grained, they are highly granitized and have a well developed foliation. Bands rich in biotite

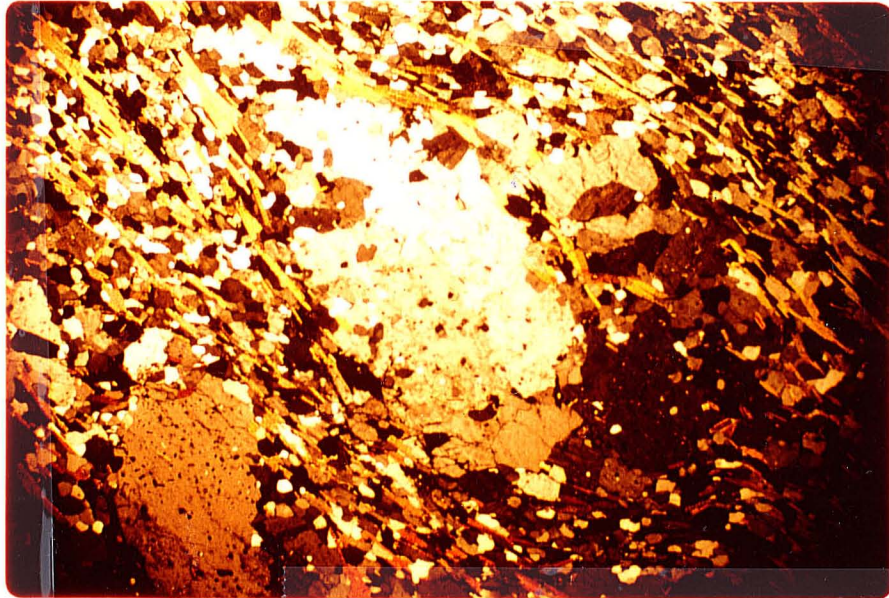


Figure 3. (x2.5) Photomicrograph of fine-grained meta-greywacke with coarse-grained rock fragments in finer-grained matrix (x nicols) SAMPLE J2.6A.

TABLE I

Estimated Mineral Composition of Selected Metasediments

| <u>Sample</u> | <u>Quartz</u> | <u>Plagioclase</u> | <u>Biotite</u> | <u>Amphibole</u> | <u>Epidote</u> | <u>Accessory Minerals</u> | <u>Total</u> |
|--------------------|---------------|--------------------|----------------|------------------|----------------|---------------------------|--------------|
| Greenstone Belt | | | | | | | |
| 0.9A* | 65 | 20 | 15 | - | - | trace | 100 |
| 0.9B* | 35 | 40 | 25 | - | - | trace | 100 |
| 0.9D ^o | 43 | 25 | 25 | - | - | 7 | 100 |
| 2.1D* | 60 | 20 | 20 | - | - | trace | 100 |
| 2.6A* | 55 | 30 | 10 | 5 | - | trace | 100 |
| 2.6B* | 47 | 25 | 15 | 10 | - | 3 | 100 |
| English River Belt | | | | | | | |
| 16.4* | 40 | 52 | 5 | - | trace | 3 | 100 |
| 19.5A* | 45 | 35 | 10 | - | trace | 10 | 100 |
| 19.5C* | 40 | 43 | 10 | - | trace | 7 | 100 |
| 28.6B* | 39 | 50 | 5 | - | 2 | 6 | 100 |
| 65B* | 55 | 30 | 15 | - | - | trace | 100 |
| 65C* | 34 | 45 | 20 | - | - | 1 | 100 |
| 65T* | 65 | 20 | 15 | - | trace | trace | 100 |
| 65X* | 60 | 30 | 10 | - | trace | trace | 100 |

Accessory Minerals are: sillimanite, sericite, magnetite, apatite, garnet, chlorite, microcline, calcite, sphene and zircon.

Greywackes represented by *

Shales represented by ^o

alternate with feldspar-quartz bands. Feldspar porphyroblasts are present in the more coarse-grained gneisses.

The English River belt paragneisses, when compared to the schists south of the boundary (Table I), contain less quartz and a correspondingly greater amount of plagioclase. Biotite content of the gneisses is slightly lower, varying between 5 - 10 per cent. The quartz content varies from 35 - 45 per cent and plagioclase from 35 - 50 per cent of the rock. Epidote is less than 1 per cent in all paragneisses (Table I). Accessory minerals are microcline, sericite, calcite, apatite, garnet, sphene, magnetite, zircon and uncommon retrograde chlorite.

A well defined equilibrium assemblage of quartz + plagioclase (range of An₂₉₋₃₆) + epidote + biotite + microcline occurs in these rocks. Retrograde alteration of biotite to chlorite is common. Corroded subhedral epidote grains in equilibrium with plagioclase and quartz are common in the gneisses.

In the vicinity of Cliff Lake, an outcrop of pyroxene granulite contains 40 per cent orthopyroxene, 20 per cent clinopyroxene, 30 per cent plagioclase, 5 per cent quartz, with accessory hornblende, magnetite, sericite and apatite. It displays a granoblastic mosaic

texture typical of rocks of the granulite facies (Figure 4). The pyroxene has been recrystallized from hornblende and contains inclusions of plagioclase and quartz (Figure 5). Tiny platy hornblende grains are present in the pyroxene, oriented parallel to the twinning. A result of retrograde alteration of pyroxene, apparently due to the presence of water which was unable to completely leave the system upon the breakdown of the amphibole. Hornblende halos around pyroxene grains are also a result of this retrograde alteration.

At Ear Falls (locality 65.0 in Figure 2) the metasediments are biotite-plagioclase-schists, containing garnet and/or retrograde chlorite in places. Fine- to medium-grained, they are similar in mineral content to the biotite-plagioclase-schists south of the English River gneissic belt; plagioclase content varies from 20 - 45 per cent, quartz 35 - 65 per cent and biotite 10 - 20 per cent of the rock, while hornblende is absent. Epidote is rare and occurs in trace amounts in samples J65A, J65B, J650 and J65X. Accessory minerals are sillimanite, magnetite, apatite, zircon and retrograde sericite.

Equilibrium assemblage of quartz + biotite + plagioclase (range of An 30 - 32 per cent) + epidote + sillimanite is common. Retrograde alteration of biotite to

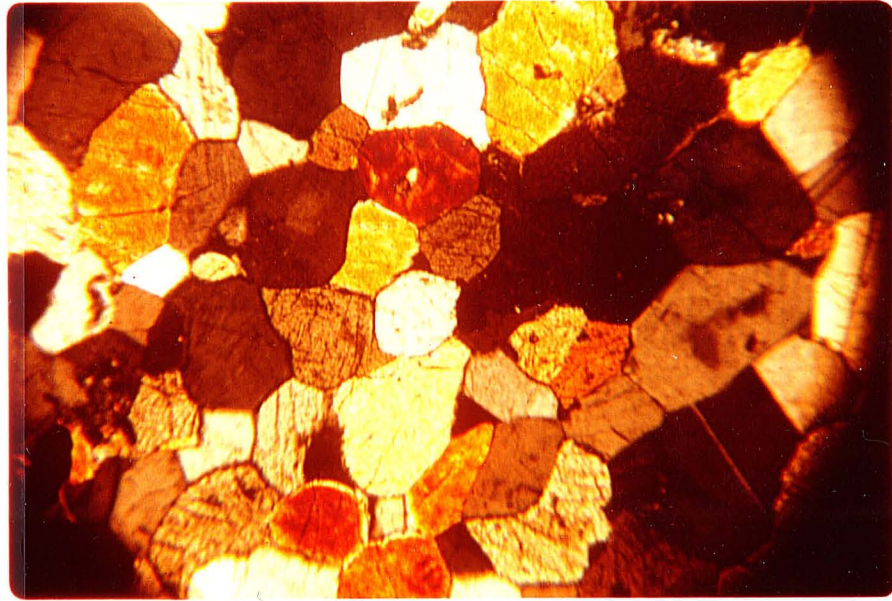


Figure 4. (x10) Photomicrograph of pyroxene granulite showing typical granoblastic mosaic texture common to rocks of the granulite facies (x nicols) SAMPLE J26.0.

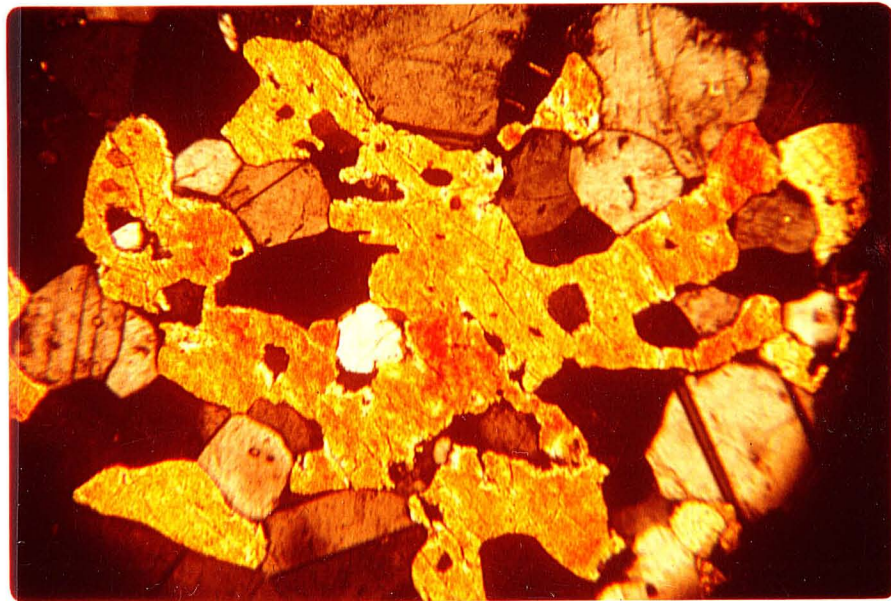


Figure 5. (x10) Photomicrograph of pyroxene granulite showing recrystallized pyroxene in center of photo (x nicols) SAMPLE J26.0.

chlorite is very common and more abundant than in the paragneisses and greenstone metasediments.

Petrochemistry

The chemical compositions of the metamorphic rocks were studied in order to determine the nature of the premetamorphic sedimentary rocks and of the environment in which they were deposited. Thirteen representative samples were analyzed for whole rock composition (Table II).

From a study of the chemical composition of sandstones, Pettijohn (1963) was able to distinguish between greywackes, shales and arkoses on the basis of whole rock composition. The average SiO_2 content of a shale is 58 per cent, whereas average greywackes contain about 65 per cent (Pettijohn, 1957). The most distinctive chemical attribute of greywacke is the excess of Na_2O over K_2O ; in shales, arkoses, slates and argillites the converse is true. Shales are composed of the finer decomposition products, therefore they lack fresh feldspar and as a result their $\text{Na}_2\text{O}/\text{K}_2\text{O}$ is less than one (Pettijohn, 1963).

Figure 6 shows the Na_2O versus K_2O contents of the analyzed rocks. Ten of the thirteen points have an

TABLE II

Whole rock chemical compositions of metasediments
(Analyses by Ken Ramlal)

| Sample No. | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | FeO | MgO | CaO | Na ₂ O | K ₂ O | H ₂ O | CO ₂ | TiO ₂ | P ₂ O ₅ | MnO | Total |
|--------------------|------------------|--------------------------------|--------------------------------|------|------|------|-------------------|------------------|------------------|-----------------|------------------|-------------------------------|------|--------|
| Greenstone Belt | | | | | | | | | | | | | | |
| J0.9B* | 58.65 | 18.69 | 1.30 | 6.12 | 3.45 | 2.53 | 3.34 | 2.82 | 1.78 | 0.22 | 0.66 | 0.13 | 0.08 | 99.77 |
| J0.9D ^o | 59.50 | 17.84 | 0.87 | 6.12 | 3.54 | 1.78 | 3.30 | 4.11 | 1.83 | 0.11 | 0.68 | 0.33 | 0.09 | 100.10 |
| J2.1D* | 70.10 | 13.03 | 1.01 | 4.24 | 2.75 | 1.99 | 2.40 | 2.40 | 1.34 | 0.08 | 0.29 | 0.13 | 0.08 | 99.83 |
| J2.6C* | 61.10 | 16.65 | 1.45 | 4.20 | 3.35 | 5.54 | 3.56 | 1.57 | 1.12 | 0.31 | 0.45 | 0.19 | 0.10 | 99.67 |
| English River Belt | | | | | | | | | | | | | | |
| J2.8A* | 61.95 | 16.48 | 2.64 | 3.16 | 1.95 | 4.57 | 4.40 | 2.13 | 0.84 | 0.06 | 0.78 | 0.33 | 0.12 | 99.40 |
| J19.5A* | 66.90 | 14.88 | 2.13 | 3.32 | 1.02 | 2.94 | 3.62 | 2.37 | 0.61 | 0.13 | 0.62 | 0.28 | 0.13 | 98.94 |
| J28.6B* | 67.95 | 15.04 | 1.55 | 2.40 | 1.10 | 3.48 | 4.60 | 1.68 | 0.70 | 0.16 | 0.51 | 0.24 | 0.08 | 99.49 |
| J65B* | 59.90 | 17.74 | 1.11 | 5.76 | 2.90 | 2.66 | 4.06 | 2.63 | 1.78 | 0.04 | 0.77 | 0.16 | 0.08 | 99.57 |
| J65B* | 68.45 | 14.23 | 1.01 | 4.44 | 2.28 | 2.42 | 3.17 | 1.78 | 1.12 | 0.37 | 0.42 | 0.11 | 0.09 | 99.89 |
| J65E ^o | 55.60 | 19.20 | 1.29 | 8.72 | 6.03 | 1.07 | 0.95 | 3.02 | 2.35 | 0.46 | 0.74 | 0.11 | 0.14 | 99.68 |
| J65O* | 55.45 | 18.42 | 1.31 | 7.92 | 3.80 | 2.21 | 3.00 | 2.08 | 3.75 | 0.56 | 0.83 | 0.24 | 0.12 | 99.27 |
| J65T* | 70.90 | 13.42 | 0.25 | 3.44 | 1.90 | 2.49 | 3.60 | 1.72 | 0.93 | 0.02 | 0.42 | 0.22 | 0.08 | 99.39 |
| J65X* | 70.15 | 13.68 | 0.66 | 3.24 | 2.40 | 2.16 | 3.32 | 2.25 | 1.23 | 0.02 | 0.46 | 0.16 | 0.10 | 99.82 |

Greywackes represented by *
Shales represented by o

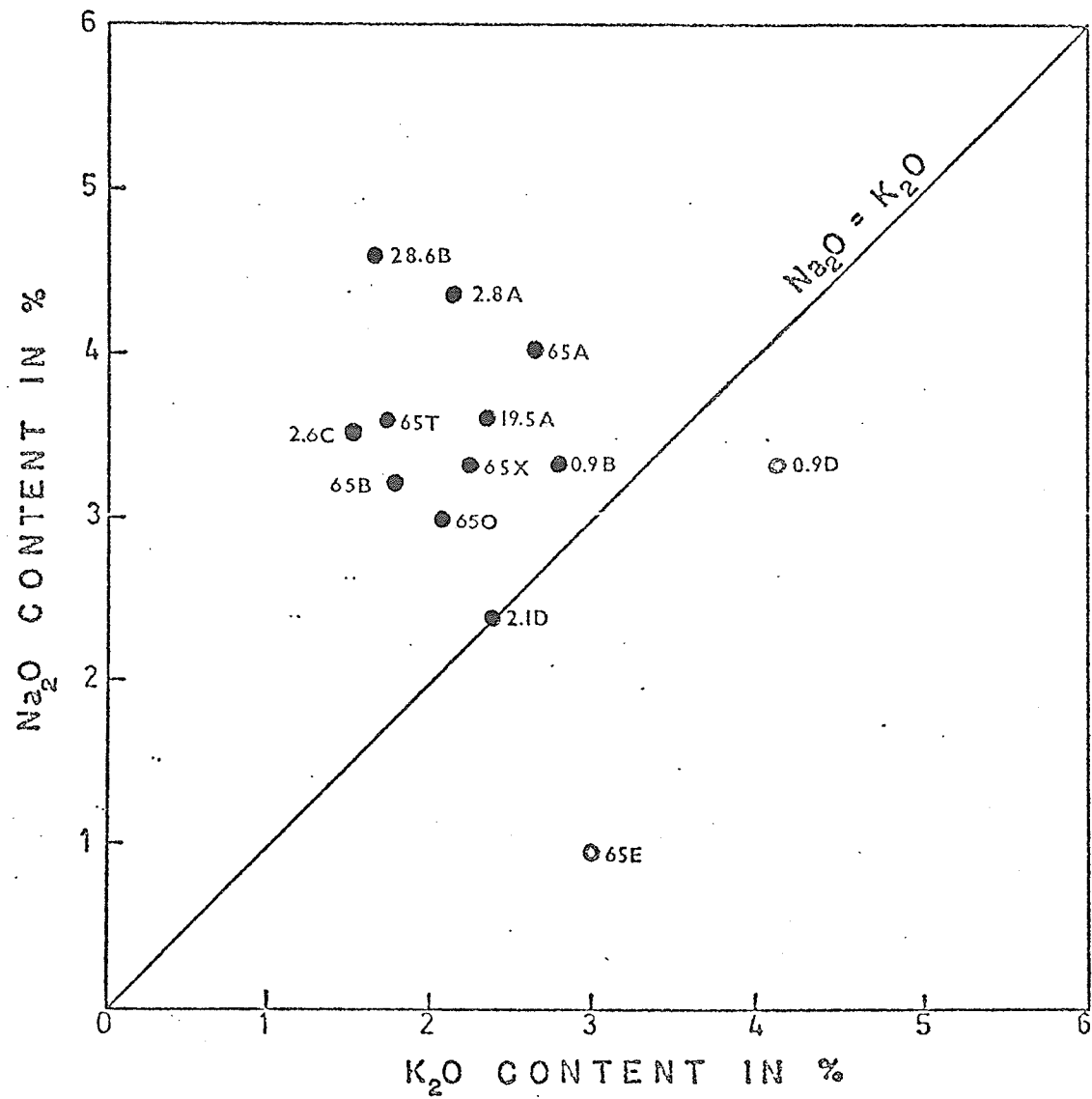


Fig. 6 . Na_2O versus K_2O content in metasediments. Greywackes are represented by filled circles. Shales are represented by empty circles.

excess of Na_2O over K_2O indicating that the rocks were originally greywackes or greywacke-like in composition. Two samples have $\text{Na}_2\text{O}/\text{K}_2\text{O}$ less than unity, which indicates they may have been originally shales or shale-like in composition.

The average silica content of those rocks which may have been originally greywackes and shales is 65.2 and 57.5 per cent respectively. These average silica contents are similar to Pettijohn's (1957) average silica content of greywackes and shales.

Figure 7 is a graph of FeO versus Fe_2O_3 , on which all points plot above the $\text{FeO} = \text{Fe}_2\text{O}_3$ line. FeO greatly exceeds Fe_2O_3 in some rocks by a factor of more than five. The shale rocks, J65E and J0.9D, have the highest values of the ratio $\text{FeO}/\text{Fe}_2\text{O}_3$.

Middleton (1960) successfully used whole rock compositions to distinguish the environments under which the rocks were deposited. Figure 8 is a plot of Al_2O_3 versus $\text{K}_2\text{O} + \text{Na}_2\text{O}$, the outlined area inside the graph representing Middleton's eugeosynclinal field for greywackes. Eight of the thirteen points fall inside Middleton's eugeosynclinal field; in the other samples the Al_2O_3 content was 1 per cent too high to fit into the field. Two of

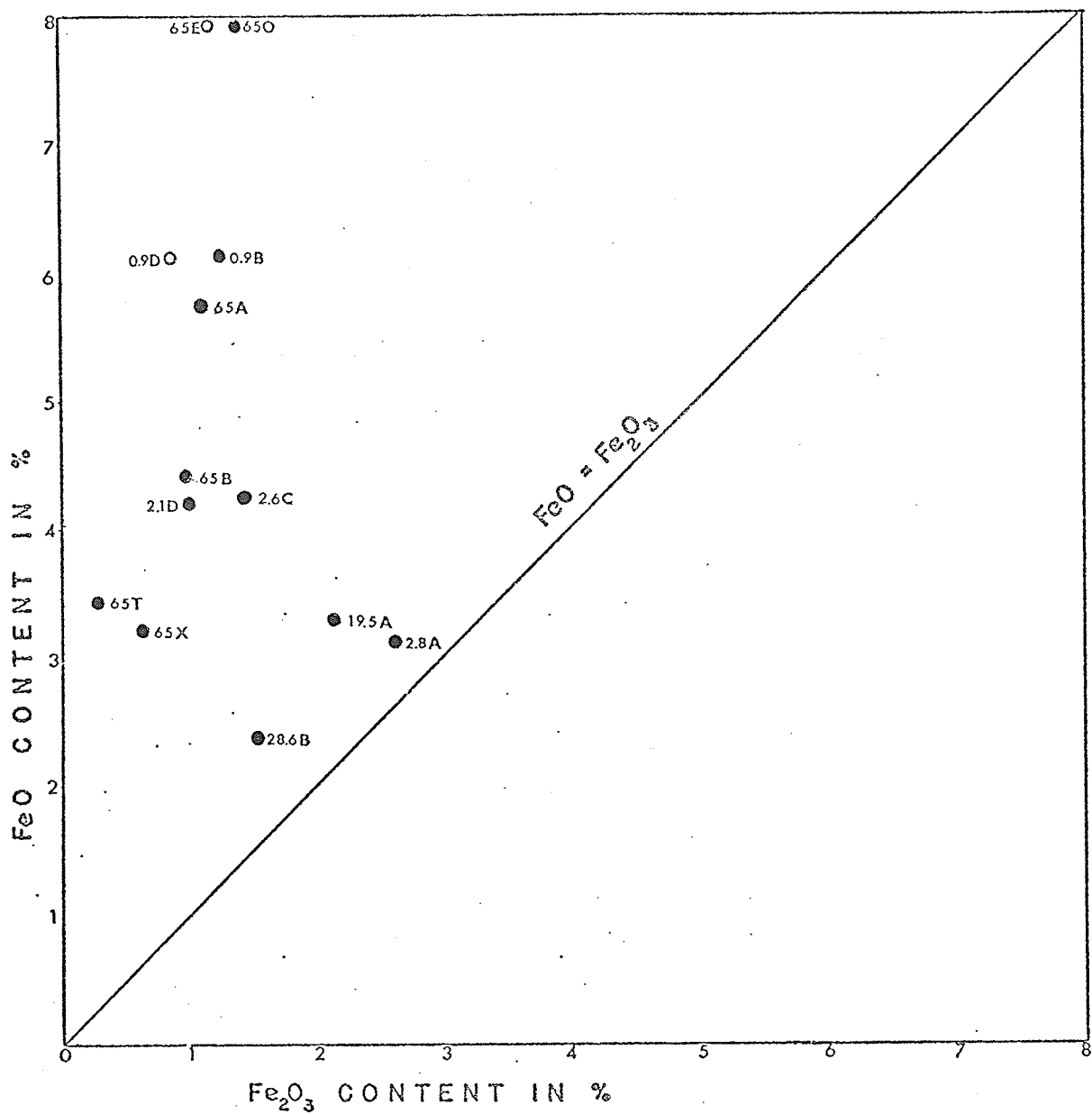


Fig. 7. FeO versus Fe₂O₃ content in metasediments. Greywackes are represented by filled circles. Shales are represented by empty circles.

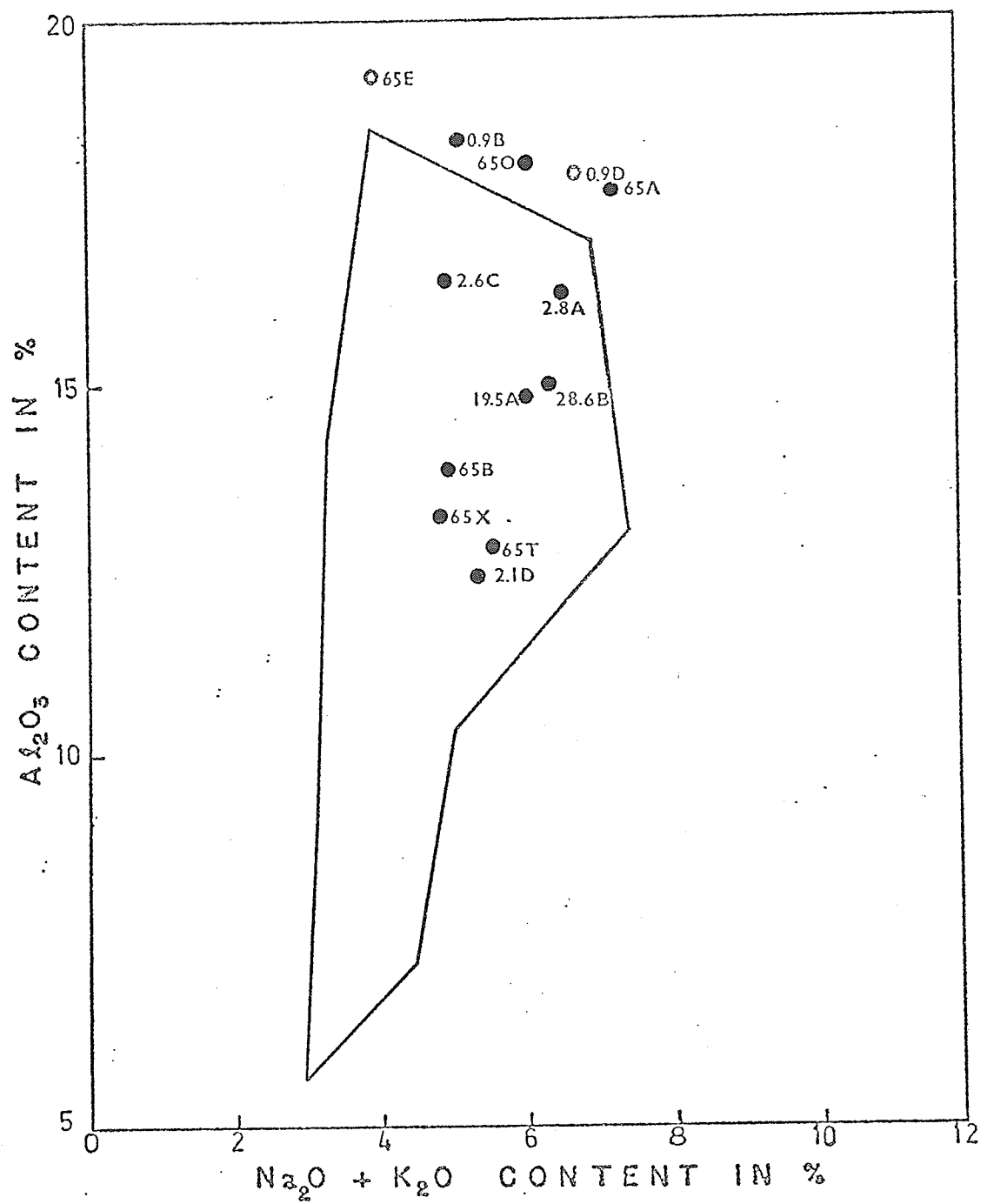


Fig. 8. Alumina-alkali variation diagram showing the distribution of metasediments in relation to the eugeosynclinal field of Middleton (1960) for greywackes. Greywackes are represented by filled circles. Shales are presented by empty circles.

the samples which plotted outside the field for greywackes also had $\text{Na}_2\text{O}/\text{K}_2\text{O}$ less than unity and were therefore originally shale-like in composition. This would account for their high Al_2O_3 content. The other three samples which fell outside Middleton's eugeosynclinal field for greywackes may have been shaly greywackes.

The ACF diagram in Figure 9 shows that the meta-sediments have similar bulk chemical composition, which makes it possible to compare their plagioclase composition.

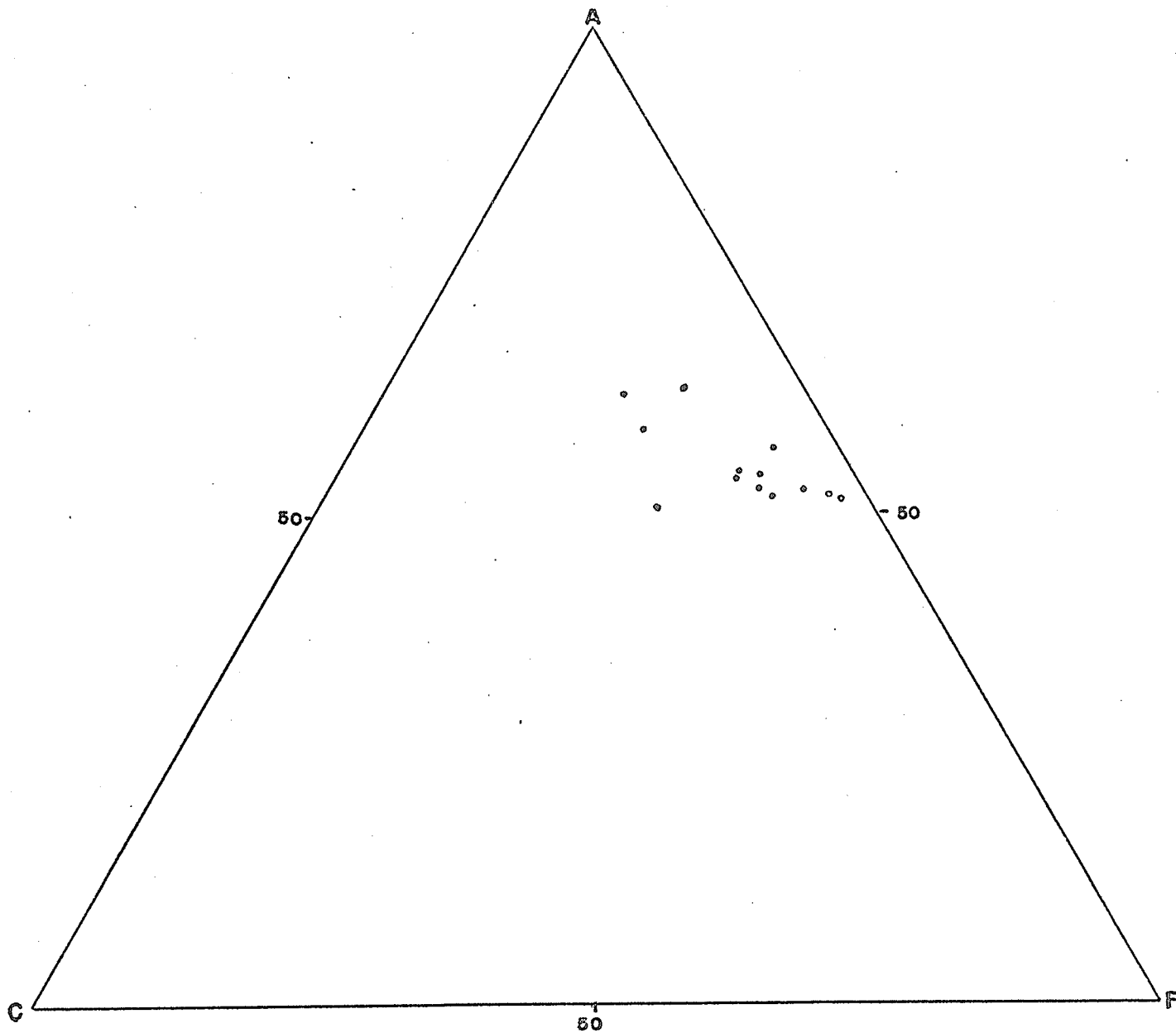


Fig. 9. Plot of the metasediments in an ACF diagram. Greywackes are represented by filled circles. Shales are represented by empty circles.

CHAPTER IV

Amphibolites

Petrography

Amphibolites occur along the Red Lake road except in the vicinity of Ear Falls, and twelve localities were sampled. In this thesis rocks containing over 40 per cent amphibole have been classified as amphibolites. Most of the brownish-grey to black outcrops are small, massive, have sharp contacts, and occur as inclusions in schists and gneisses. Amphibolites which contained at least 10 per cent more plagioclase than quartz have been classified as plagioclase amphibolites; the majority of the amphibolites in the area are of this type. Those amphibolites which contained more than 10 per cent pyroxene have been classified as pyroxene-amphibolites. Four of the twelve amphibolites studied contained at least 10 per cent pyroxene. The term amphibolite, in this sense, is not being used to designate the amphibolite facies.

Amphibolites south of the fault zone boundary in the greenstone belt are very fine grained and finely

banded. On the average, they contain a higher proportion of amphibole than those amphibolites in the English River gneissic belt. They contain 40 - 70 per cent amphibole, 5 - 40 per cent plagioclase, and 10 - 30 per cent quartz. Pyroxene, which occurs in veins, can be as high as 25 per cent of the rock (Table III). Epidote, calcite, garnet, magnetite, apatite, sphene and sulphides are common accessory minerals.

Hornblende is pleochroic green. Biotite is brown with high pleochroism. The pyroxene is monoclinic and weakly pleochroic. The amphibolites have a very well-developed granoblastic texture except where biotite is present. With biotite present the rocks are coarser grained and contain large porphyroblasts of hornblende with smaller-sized plagioclase grains (Figure 10).

The common equilibrium assemblage is hornblende + plagioclase + quartz + epidote \pm pyroxene \pm biotite. Retrograde alteration is minor, with hornblende partly altered to biotite and pyroxene partly altered to amphibole.

The amphibolites within the English River belt are medium-grained and more massive than those from south of the boundary, and they occur, generally, as inclusions in gneisses. Their amphibole and quartz contents

TABLE III

Estimated Mineral Composition of Selected Amphibolites

| <u>Sample</u> | <u>Plagioclase</u> | <u>Amphibole</u> | <u>Quartz</u> | <u>Biotite</u> | <u>Pyroxene</u> | <u>Accessory Minerals</u> | <u>Total</u> |
|--------------------|--------------------|------------------|---------------|----------------|-----------------|---------------------------|--------------|
| Greenstone Belt | | | | | | | |
| 1.6A | 5 | 45 | 20 | 5 | 25 | trace | 100 |
| 1.6C | 10 | 70 | 15 | 5 | - | trace | 100 |
| 2.6D | 20 | 70 | 10 | - | - | trace | 100 |
| 2.6E | 28 | 60 | 10 | - | - | 2 | 100 |
| English River Belt | | | | | | | |
| 11.2 | 35 | 40 | 20 | 2 | 1 | 2 | 100 |
| 22.1 | 30 | 40 | 5 | - | 25 | trace | 100 |
| 31B | 40 | 40 | 9 | 1 | 10 | trace | 100 |
| 36.1 | 40 | 40 | 4 | - | 15 | 1 | 100 |

Accessory Minerals are: epidote, chlorite, calcite, garnet, sericite, magnetite, apatite, sphene and sulphides.



Figure 10. (x2.5) Photomicrograph of amphibolite south of the English River belt showing coarse-grained hornblende porphyroblasts in fine-grained amphibolite (x nicols) SAMPLE J1.6C.

are lower and plagioclase content on the average is higher. Amphibole content varies between 40 - 50 per cent, plagioclase 30 - 40 per cent and quartz 5 - 20 per cent. Clinopyroxene constitutes as much as 10 - 25 per cent of the rock. Biotite content is similar to that of the greenstone belt amphibolites. Accessory minerals are epidote, magnetite, apatite, sericite, sphene and retrograde chlorite.

In thin section it is evident that the pyroxene has resulted from the breakdown of hornblende. However, the water set free by the partial breakdown of hornblende may have been unable to leave the system. As a result, the water pressure increased and most of the hornblende was therefore preserved (Figures 11 - 13). Platy hornblende parallel to the twinning planes in the pyroxene is considered to be evidence that some hornblende has formed at the expense of the pyroxene under retrograde conditions. Minor retrograde alteration of biotite to chlorite occurs in most amphibolites. The equilibrium assemblage is hornblende + plagioclase + epidote + quartz \pm pyroxene \pm biotite.

Petrochemistry

Chemical analyses of eight samples of amphibolite,

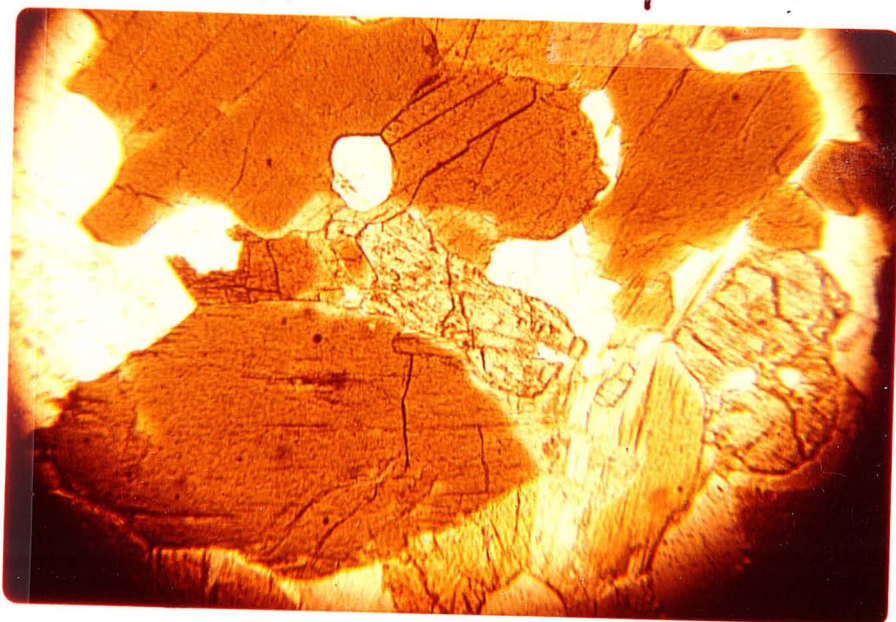


Figure 11. (x10) Photomicrograph of pyroxene-amphibolite showing hornblende partly replaced by pyroxene (plain light) SAMPLE J31B.

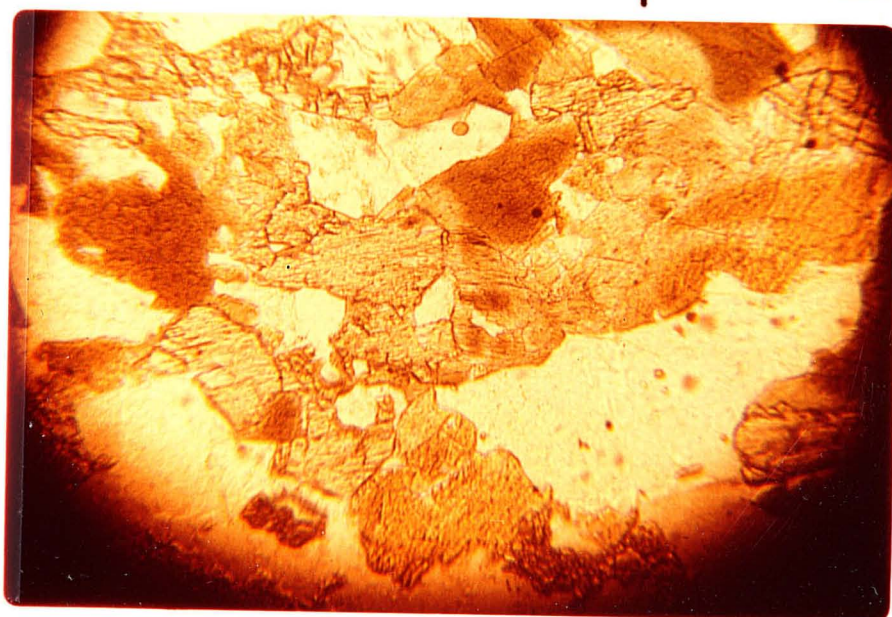


Figure 12. (x10) Photomicrograph of pyroxene-amphibolite showing hornblende almost completely replaced by pyroxene (plain light) SAMPLE J31B.

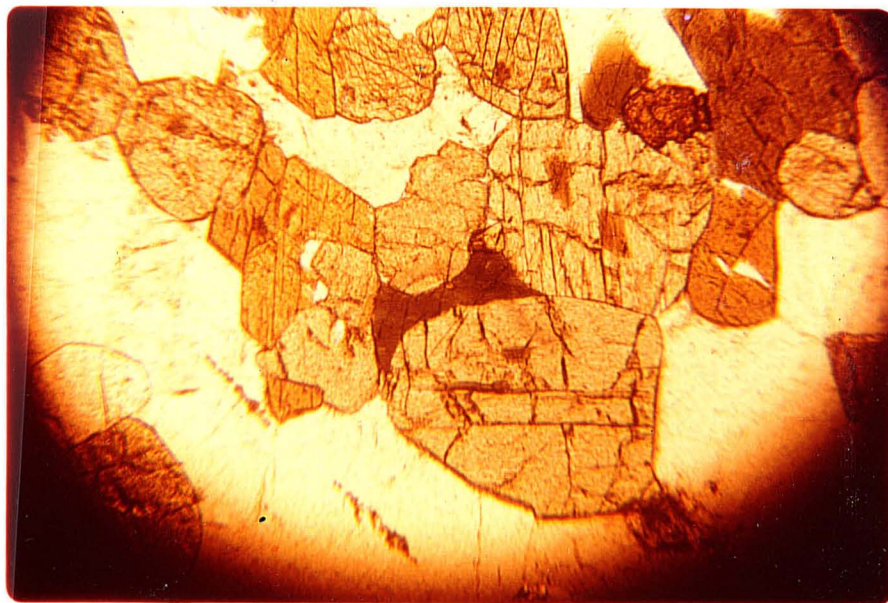


Figure 13. (x10) Photomicrograph of pyroxene-amphibolite showing two adjacent pyroxene grains, each of which contains two small grains of retrograde hornblende parallel to the pyroxene twinning planes. (Plain Light). SAMPLE J36.1.

representative of their occurrences in the greenstone belt and in the English River belt, are presented in Table IV.

The distinction between para- and ortho-amphibolites should be based more on the trends of variation in the contents of the oxides and not so much on the absolute concentration of certain elements, and on a comparison of these trends to known igneous and sedimentary trends (Leake, 1964). Nearly all the major elements would be similar in concentration whether the rocks had formed by the metamorphism of basic igneous rocks or by the metamorphism of a dolomite or calcareous clay (Leake, 1964). Banding cannot be used as a reliable indicator of a sedimentary origin. Metamorphic segregation, shearing and tectonic thinning of interbedded sequences could account for the banded appearance.

Some ortho-amphibolites can be distinguished from para-amphibolites by a systematic decrease in $\underline{mg} = \text{MgO}/(\text{FeO} + 2\text{Fe}_2\text{O}_3 + \text{MnO} + \text{MgO})$ with increase in silica, alkalis, alumina and titanium, which is commonly associated with magmatic differentiation in basic magmas. The changes in $\underline{c} = 100 \times \text{CaO}/(\text{CaO} + \text{MgO} + \text{FeO} + 2\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3)$ with change in \underline{mg} are variable depending mainly on the stage

TABLE IV

Whole rock chemical compositions of amphibolites
(Analyses by Ken Ramlal)

| <u>Sample No.</u> | <u>SiO₂</u> | <u>Al₂O₃</u> | <u>Fe₂O₃</u> | <u>FeO</u> | <u>MgO</u> | <u>CaO</u> | <u>Na₂O</u> | <u>K₂O</u> | <u>H₂O</u> | <u>Co₂</u> | <u>TiO₂</u> | <u>P₂O₅</u> | <u>MnO</u> | <u>Total</u> |
|--------------------|------------------------|------------------------------------|------------------------------------|------------|------------|------------|------------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------------------|------------|--------------|
| Greenstone Belt | | | | | | | | | | | | | | |
| J2.6D | 46.35 | 12.69 | 3.77 | 13.36 | 5.75 | 10.22 | 2.78 | 0.40 | 1.44 | 0.11 | 2.28 | 0.19 | 0.24 | 99.58 |
| J2.6F | 49.65 | 14.33 | 2.85 | 11.36 | 4.60 | 9.17 | 3.38 | 0.33 | 1.13 | 0.18 | 1.94 | 0.24 | 0.22 | 99.38 |
| J2.6G | 44.95 | 13.63 | 3.15 | 15.08 | 5.07 | 9.85 | 2.78 | 0.46 | 1.64 | 0.32 | 2.07 | 0.61 | 0.51 | 100.00 |
| English River Belt | | | | | | | | | | | | | | |
| J11.2 | 53.50 | 13.04 | 3.12 | 6.16 | 7.80 | 8.69 | 3.40 | 1.02 | 1.54 | 0.26 | 0.63 | 0.22 | 0.16 | 99.54 |
| J22.1 | 48.40 | 13.02 | 3.04 | 9.36 | 8.13 | 12.04 | 2.70 | 0.62 | 0.94 | 0.13 | 0.77 | 0.13 | 0.20 | 99.48 |
| J28.6D | 46.05 | 14.16 | 3.80 | 8.20 | 9.00 | 11.84 | 2.96 | 0.78 | 1.40 | 0.08 | 0.80 | 0.15 | 0.28 | 98.90 |
| J31B | 47.30 | 14.10 | 3.82 | 8.40 | 9.15 | 11.06 | 2.71 | 0.74 | 1.50 | 0.16 | 0.60 | 0.11 | 0.19 | 99.84 |
| J36.1 | 52.15 | 13.98 | 2.58 | 11.84 | 3.25 | 8.62 | 2.95 | 0.43 | 1.14 | 0.22 | 1.87 | 0.21 | 0.32 | 99.56 |

of the differentiation (Leake, 1964). The trends given by mixtures of pelite with limestone and/or dolomite on a plot of mg against c are approximately at right angles to the trend given by basic igneous rocks and therefore comparison of mg versus c plots can help distinguish the difference between para- and ortho-amphibolites.

Figure 14 is a mg versus c diagram, as used by Leake (1964), with the eight amphibolite samples plotted. The eight points fall along the trend line of basic igneous rocks. There are two clusters of points, giving an imperfect separation between points from within the greenstone belt and those from within the gneissic belt. The greenstone amphibolites are at the late-stage-differentiates part of the line. The amphibolites from within the English River belt plot as late- to middle-stage-differentiates.

A triangular plot of the values mg, c and al-alk, also used by Leake (1964), is shown in Figure 15. The arrow again represents the trend line of basic igneous rocks. Mixtures of pelite and semi-pelite with limestone not only plot in a different part of the diagram but they also have a characteristic trend of their own. The eight points again closely follow the trend

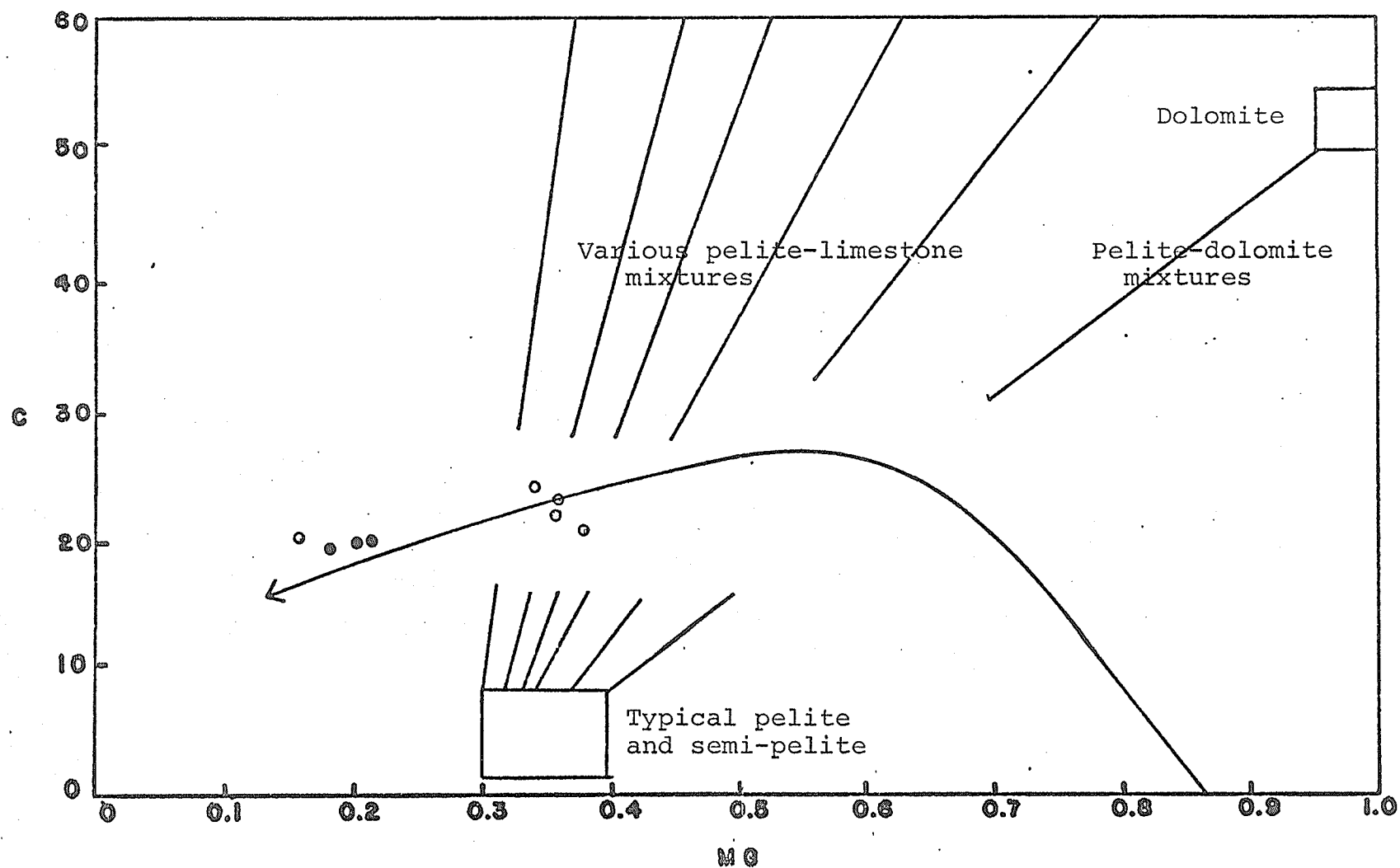


Fig. 14. Niggli *mg* versus *c* plot. Solid line with arrow indicates the trend line for basic igneous rocks. Broken lines indicate various limestone-dolomite mixtures mixed with varying amounts of typical pelite and semi-pelite. Greenstone belt specimens are represented by filled circles. English River belt specimens are represented by empty circles. After Leake (1964).

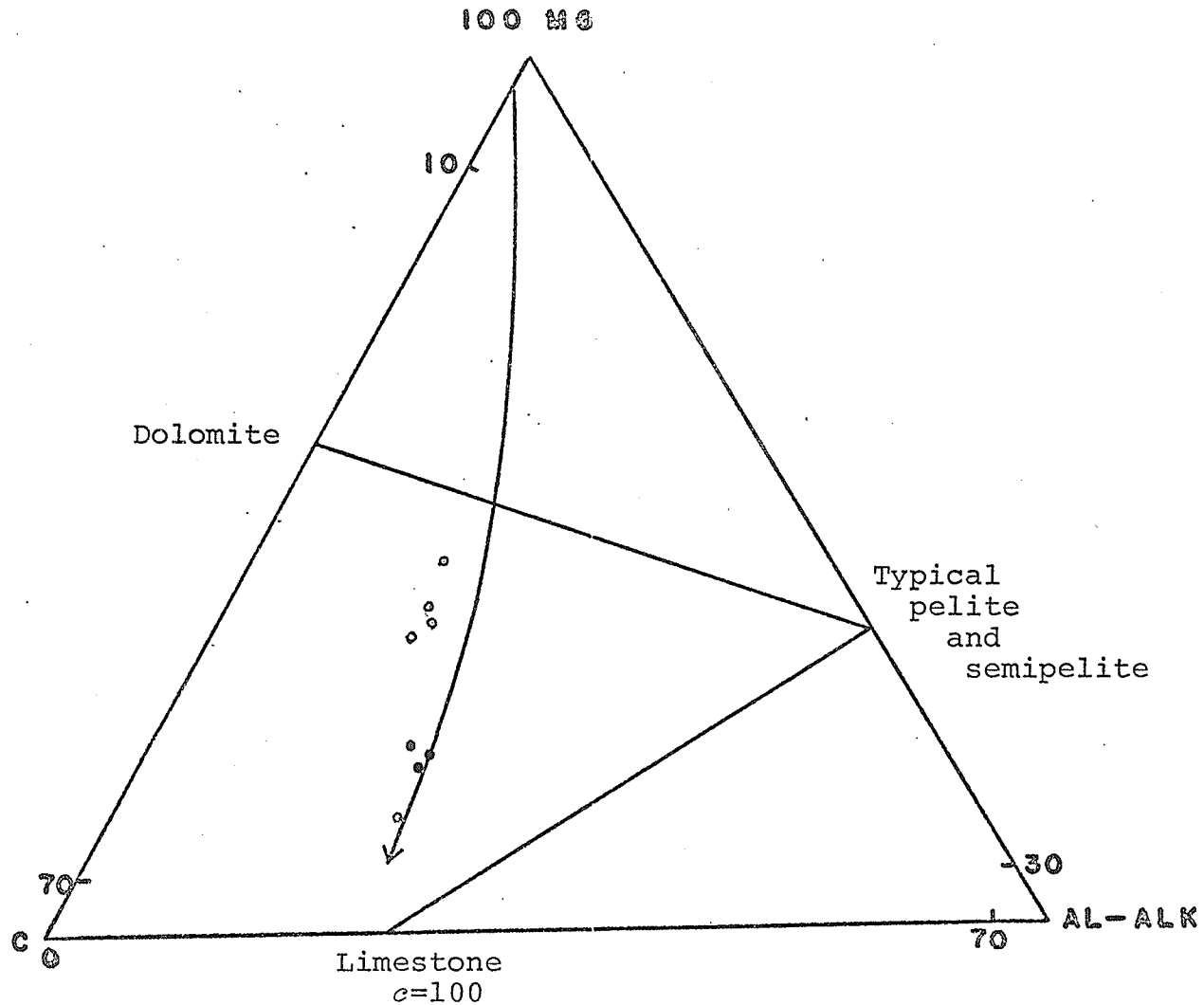


Fig. 15. Part of the 100 mg, c and (al-alk) triangle. Solid line with arrow represents the trend line of basic igneous rocks. Greenstone belt amphibolites are represented by filled circles. English River belt amphibolites are represented by empty circles. After Leake (1964).

line of basic igneous rocks. As before, there are two clusters of points; those within the greenstone belt are late basic igneous rocks and those within the English River belt are between early and late basic igneous rocks.

An ACF diagram (Figure 16) has been plotted to show the uniform bulk chemical composition. Therefore, the anorthite content of their plagioclases can be used for determination of metamorphic grade.

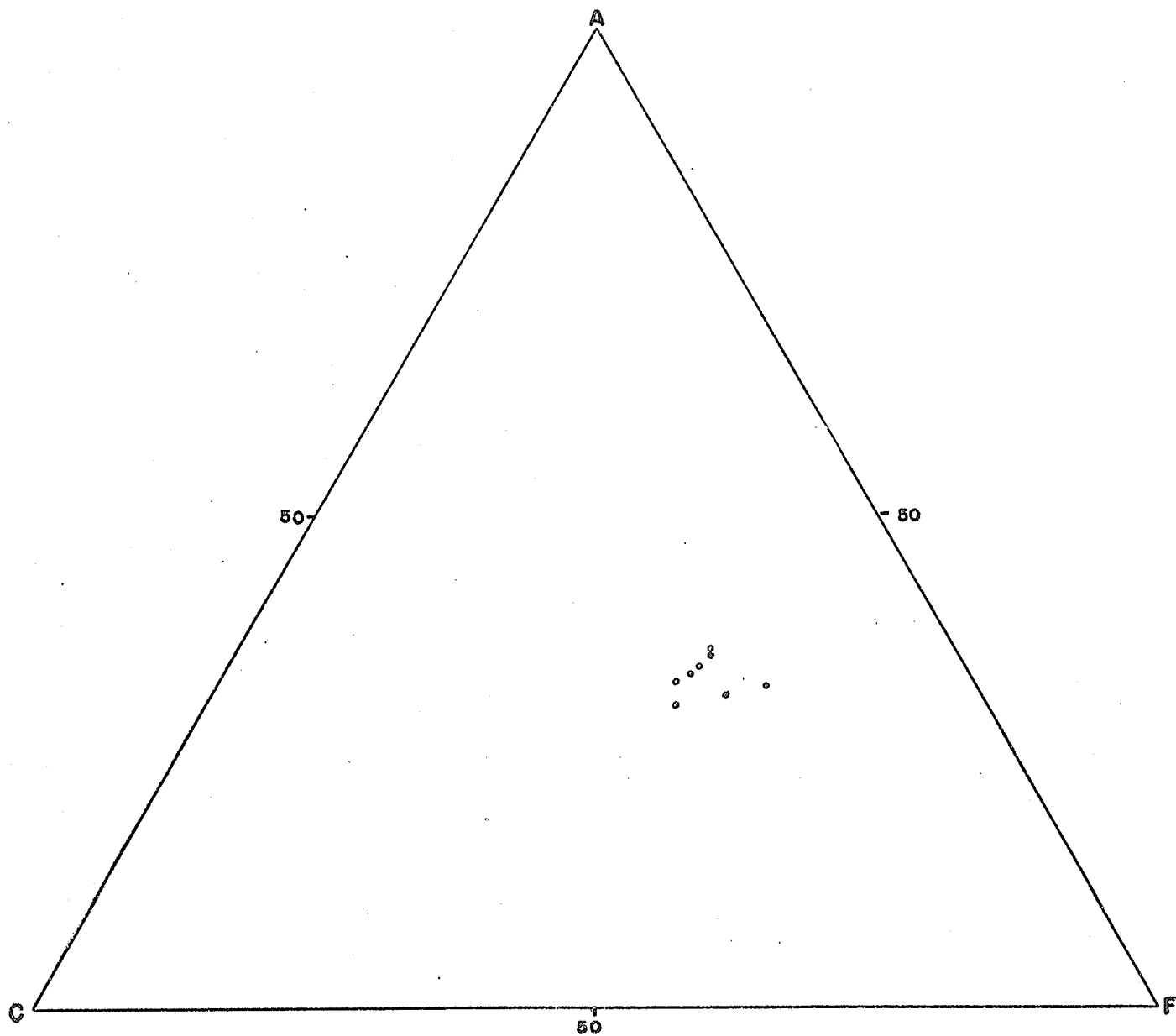


Fig. 16. Plot of the amphibolites in an ACF diagram. Greenstone belt amphibolites are represented by filled circles. English River belt amphibolites are represented by empty circles.

CHAPTER V

Granitic Intrusions

Petrography

As the purpose of this work was to study the metamorphism across the English River belt, little time was spent studying the granitic intrusions, even though they are the most abundant rock types exposed in the area. Granites, granodiorites, quartz monzonites, and quartz diorites were found along the Red Lake road. They occur as massive grey and pink weathering intrusions, elongated parallel to the trends of the sedimentary rocks.

Typical mineral assemblages are quartz, microcline, oligoclase, biotite and, rarely, hornblende. Plagioclase is altered slightly to sericite but the potash feldspar is unaltered. Microcline in all examined rocks displays typical cross-hatched twinning. Plagioclase is subhedral to anhedral and shows albite and pericline twins. Myrmekitic intergrowths of plagioclase and quartz are rare, but were observed in the granodiorites.

The mafic minerals are responsible for any

slight foliation which might be present. Biotite is present in all the types, varying between 2 - 10 per cent of the rock with the greatest concentration occurring in the quartz diorites. The color of biotite is brown or green and in most rocks has undergone retrograde alteration to chlorite. Hornblende was found only in the quartz diorites.

Accessory minerals present are garnet, sericite, epidote, magnetite, apatite, calcite, zircon, and sphene.

Petrochemistry

A representative sample of each granitic rock type found along the Red Lake road was analyzed for whole rock composition (Table V). Notable differences in composition were not present among the different rock types, with the exception of quartz diorite. The granodiorite and quartz monzonite averaged 73 per cent silica, the silica content of the quartz diorite was 65 per cent. The CaO, MgO, and total Fe content of the quartz diorite is larger than those of the other rock types by a factor of four. Only 1 per cent potassium feldspar occurs in the quartz diorite, compared to 20 - 35 per cent in the other rock types. The Na₂O contents were roughly the same for all granitic rock-types analysed.

TABLE V

Whole rock chemical compositions of selected granitic rocks and of a sample of quartz diorite.
(Analyses by Ken Ramlal)

| <u>Rock Type</u> | <u>Sample No.</u> | <u>SiO₂</u> | <u>Al₂O₃</u> | <u>Fe₂O₃</u> | <u>FeO</u> | <u>MgO</u> | <u>CaO</u> | <u>Na₂O</u> | <u>K₂O</u> | <u>H₂O</u> | <u>CO₂</u> | <u>TiO₂</u> | <u>P₂O₅</u> | <u>MnO</u> | <u>Total</u> |
|---------------------|-------------------|------------------------|------------------------------------|------------------------------------|------------|------------|------------|------------------------|-----------------------|-----------------------|-----------------------|------------------------|-----------------------------------|------------|--------------|
| Quartz Diorite | J2.8B | 65.35 | 16.60 | 1.40 | 2.40 | 1.95 | 4.36 | 4.02 | 1.79 | 0.870 | 0.035 | 0.50 | 0.23 | 0.062 | 99.56 |
| Granodiorite | J2.8C | 73.15 | 14.78 | 0.21 | 0.60 | 0.31 | 1.40 | 3.90 | 4.37 | 0.62 | 0.19 | 0.04 | 0.07 | 0.025 | 99.66 |
| Quartz Monzonite | J2.8F | 75.25 | 13.96 | 0.14 | 0.84 | 0.21 | 0.48 | 3.08 | 5.46 | 0.60 | 0.09 | 0.01 | 0.07 | 0.093 | 100.19 |
| Granite | J28.6A | 71.90 | 14.93 | 0.01 | 0.72 | 0.28 | 1.63 | 3.68 | 5.67 | 0.505 | 0.175 | 0.10 | 0.07 | 0.036 | 99.74 |

CHAPTER VI

Metamorphism and Anorthite Content

Three types of assemblages were studied for composition of plagioclase. Type 1 assemblage was for metasedimentary rocks which did not contain epidote. Type 2 assemblage was for metasedimentary rocks which did contain epidote. Type 3 assemblage was for amphibolites which did contain epidote.

Within the greenstone belt to the south of the English River gneisses anorthite contents of the plagioclases within two amphibolites average 38 per cent, indicating andesine-epidote-amphibolite facies. Type 1 metasediments in this area have anorthite contents of 30 per cent, also indicating the upper amphibolite facies. The lower anorthite values for the Type 1 metasediments may be due to an absence of epidote. If insufficient epidote is present the reaction cannot proceed, and the anorthite content of the plagioclases can therefore only give the minimum grade of metamorphism. The lower anorthite values and absence of epidote in the metasediments could be due to an initial lower CaO content.

At mileage 11.2, in the southern portion of the

English River belt, plagioclase from an amphibolite had an anorthite content of 36 per cent. Two Type 2 paragneisses, at 16.4 and 19.5 miles along the Red Lake road, had anorthite contents of 29 and 31 per cent respectively. The grade of metamorphism, then, in the southern portion of the belt is andesine-epidote-amphibolite facies, the same as that of the greenstone belt.

Two miles south of Cliff Lake clinopyroxene was observed in an amphibolite. Textural characteristics showed the clinopyroxene was a result of replacement of hornblende, which is indicative of the granulite facies of metamorphism (Figures 17 and 18). The pyroxene-amphibolite also has the typical granoblastic texture common to rocks of the granulite facies. The anorthite content of the plagioclase in this sample (52 per cent) is higher than the upper limit of amphibolite facies and therefore indicates the hornblende-clinopyroxene-plagioclase subfacies of metamorphism. At Cliff Lake where an outcrop of pyroxene-granulite is present, the anorthite content of the plagioclase was the highest found in the area (66 per cent), which is well above the anorthite limit of upper amphibolite facies. The hornblende has been completely replaced by mainly orthopyroxene and clinopyroxene,

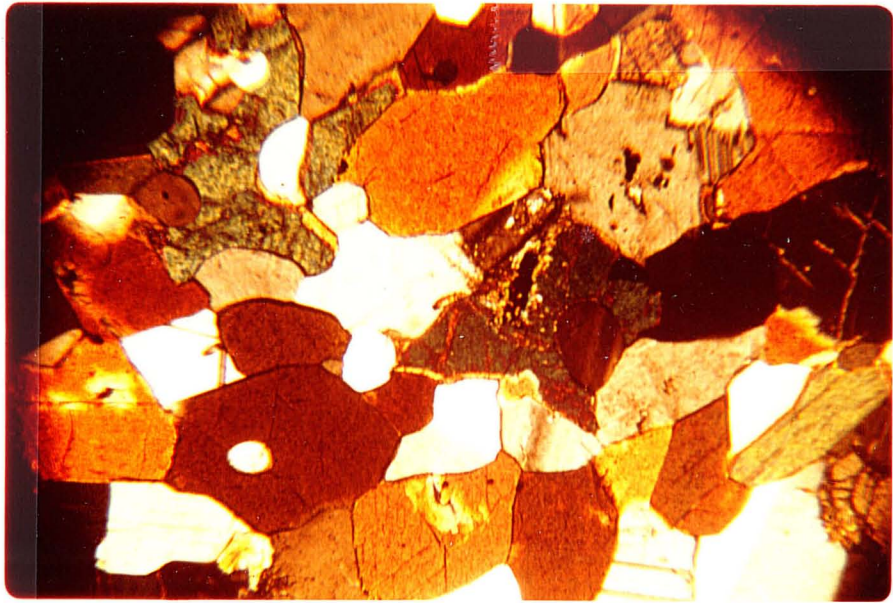


Figure 17. (x10) Photomicrograph of pyroxene-amphibolite showing typical granoblastic texture common to rocks of the granulite facies of metamorphism (x nicols) SAMPLE J22.1.

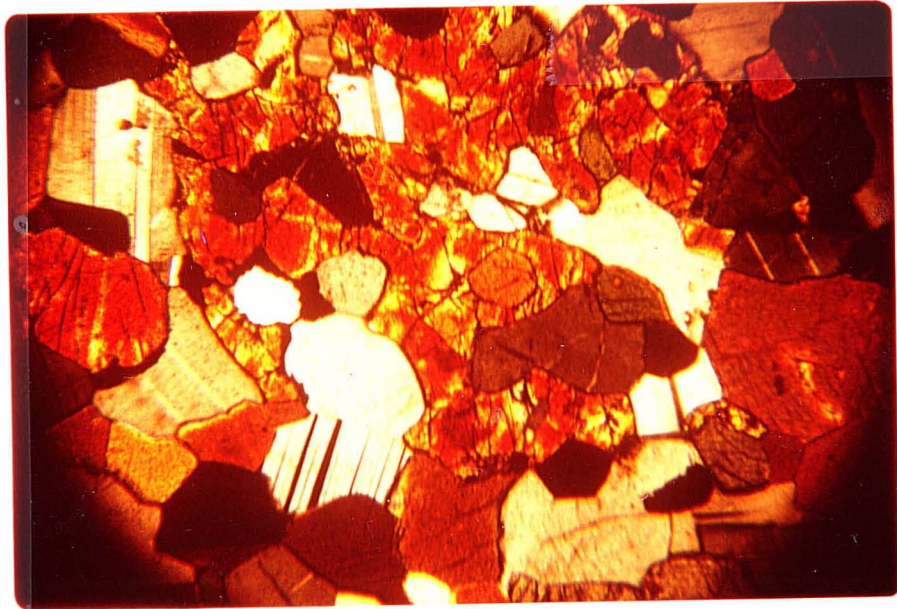


Figure 18. (x10) Photomicrograph of pyroxene-amphibolite showing orthopyroxene with numerous inclusions (x nicols) SAMPLE J22.1.

except for minor amounts of hornblende which are a result of retrograde alteration of the pyroxene grains. Therefore, at mileage 26.0 the grade of metamorphism is hornblende-orthopyroxene-plagioclase granulite subfacies.

A Type 2 metasediment and an amphibolite sample taken at mileage 28.6, which is at Cedar Lake, had plagioclase anorthite contents of 36 and 44 per cent respectively. No pyroxene was present in the amphibolite. Metamorphic grade has therefore decreased from the granulite facies at Cliff Lake to the upper amphibolite facies at Cedar Lake.

Amphibolites collected at mileage 31.0 and 36.1 contained recrystallized pyroxene. These two samples have been classified as pyroxene-amphibolites because they contain over 40 per cent amphibole. However, their plagioclase anorthite contents of 48 per cent are higher than the 45 per cent upper limit of the amphibolite facies, and the presence of hornblende partly replaced by clinopyroxene places them in the hornblende-clinopyroxene granulite subfacies of metamorphism. Unfortunately no metasedimentary outcrops were present between mileage 28.6 and Ear Falls which could give anorthite contents to back up the data obtained from the amphibolites. From mileage 36.0 to Ear Falls, no amphibolites or metasediments were observed which

could be useful in determining grade of metamorphism.

At Ear Falls (mileage 65.0) six Type 2 metasediments were checked for anorthite content of their plagioclases. Results were from 30 - 32 per cent anorthite. Sillimanite is present in minor amounts in these rocks (Figures 19, 20). From mileage 36.0 to Ear Falls, the grade of metamorphism has therefore decreased from granulite facies to andesine-amphibolite subfacies.

Figure 21 is a plot of anorthite content of the plagioclases in the amphibolites and metasediments versus mileage along the Red Lake road. From the amphibolite plot it can be seen that there is a considerable increase in the anorthite content between 11.2 and 22.0 miles. This is also reflected in the metasediment plot which indicates a rise between 19.4 and 26.0 miles. This rise, coupled with the appearance of recrystallized pyroxene at 22.0 and 26.0 miles is definite evidence that the metamorphic grade has increased, at least to the granulite facies, between 22.0 and 26.0 miles. Both plots show an anorthite content decrease between 26.0 and 28.6 miles. Since pyroxene is absent in the amphibolite at 28.6 miles the grade of metamorphism has decreased to upper amphibolite facies. No data on the anorthite contents of plagioclases

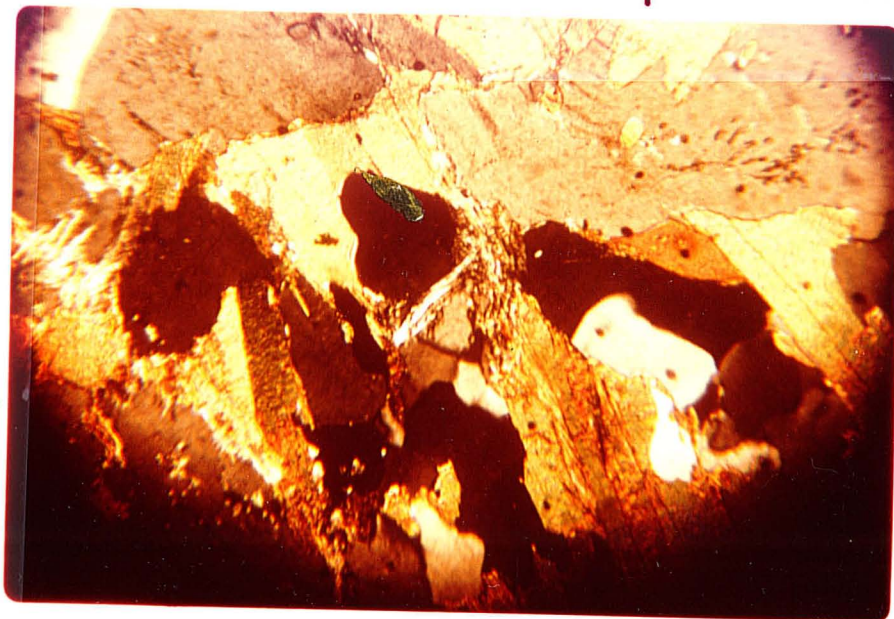


Figure 19. (x10) Photomicrograph of metasediment at Ear Falls showing clotted sillimanite in center of photo (x nicols) SAMPLE J65A.

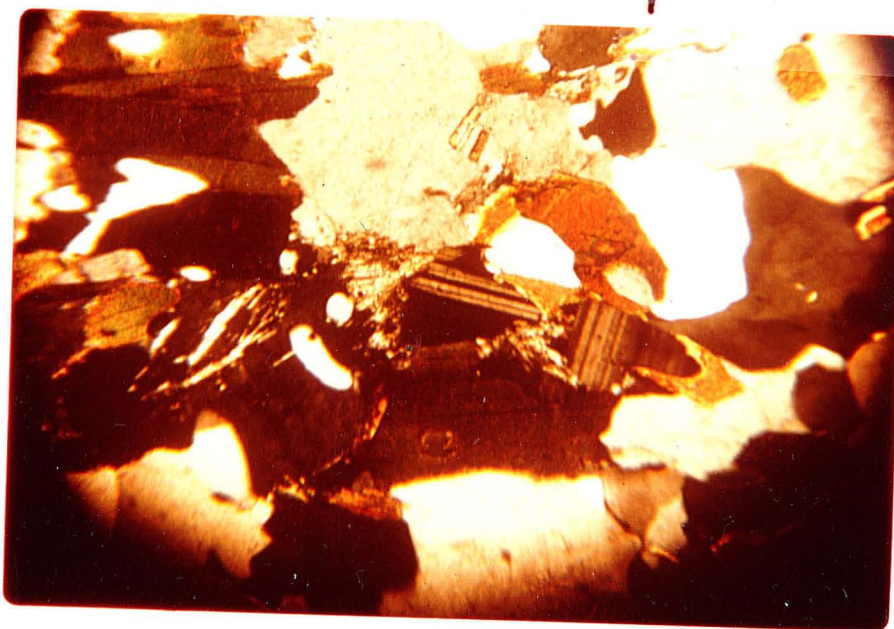


Figure 20. (x10) Photomicrograph of metasediment at Ear Falls containing sillimanite around plagioclase grain (x nicols) SAMPLE J65A.

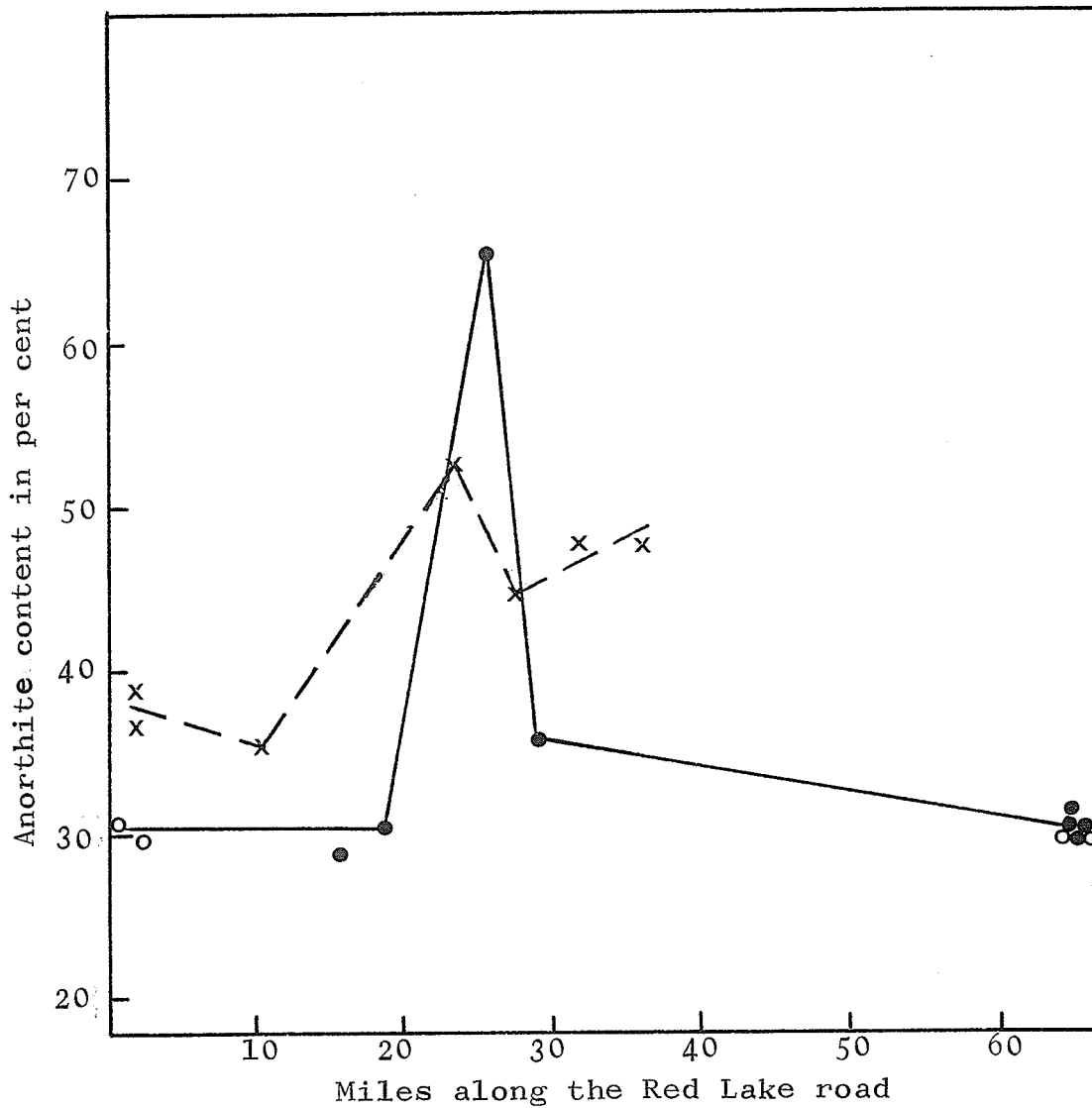


Figure 21. Graph of anorthite content of plagioclase for amphibolites and metasediments versus mileage along the Red Lake road. Metasediments containing epidote represented by solid circles. Metasediments without epidote represented by empty circles. Amphibolites represented by crosses.

for metasedimentary rocks are available between 28.6 to 65.0 miles. Therefore, nothing more can be inferred from this plot except that, at Ear Falls itself, the grade is upper amphibolite facies. The amphibolite plot, however, shows two points at 31.0 and 36.1 miles both above the anorthite 45 per cent. They also both contain recrystallized pyroxene. It can be inferred then, that from 28.6 to 31.0 miles the grade has increased to granulite facies, and that at 65.0 miles the grade has decreased to andesine-amphibolite subfacies.

The similarity between the two plots for the two different rock types suggests that the anorthite changes encountered along the Red Lake road are a reflection of metamorphism as only rocks of equal bulk chemical composition have been compared. Also, the fact that pyroxene has replaced hornblende in those samples which plot above the 45 per cent level strongly suggests that the anorthite content of plagioclase is a reliable indicator of metamorphic grade.

CHAPTER VII

Summary and Conclusions

The metamorphic grade across the English River belt is upper amphibolite facies, increasing locally in the central portion of the belt to granulite facies, as shown in Figure 22. Locally granulites and pyroxene bearing amphibolites occur in the central portion of the belt, suggesting higher temperatures than those active in the southern and northern portions of the belt. The temperatures in places could have been as high as 800°C. There does not appear to be a continuous zone or area of granulite facies metamorphism. In some areas the temperature and pressure were sufficient to cause recrystallization of pyroxene and raise the anorthite content of plagioclase above the upper amphibolite facies limit, but the extent of these areas is rather small.

The presence or absence of hornblende within rocks of the granulite facies is attributed not to a difference in temperature under equal pressure, but rather to different original water contents and to metamorphism under essentially closed-system conditions (Winkler, 1967). In the pyroxene bearing amphibolites, which appear to be igneous in origin, the water which was released by the partial breakdown of

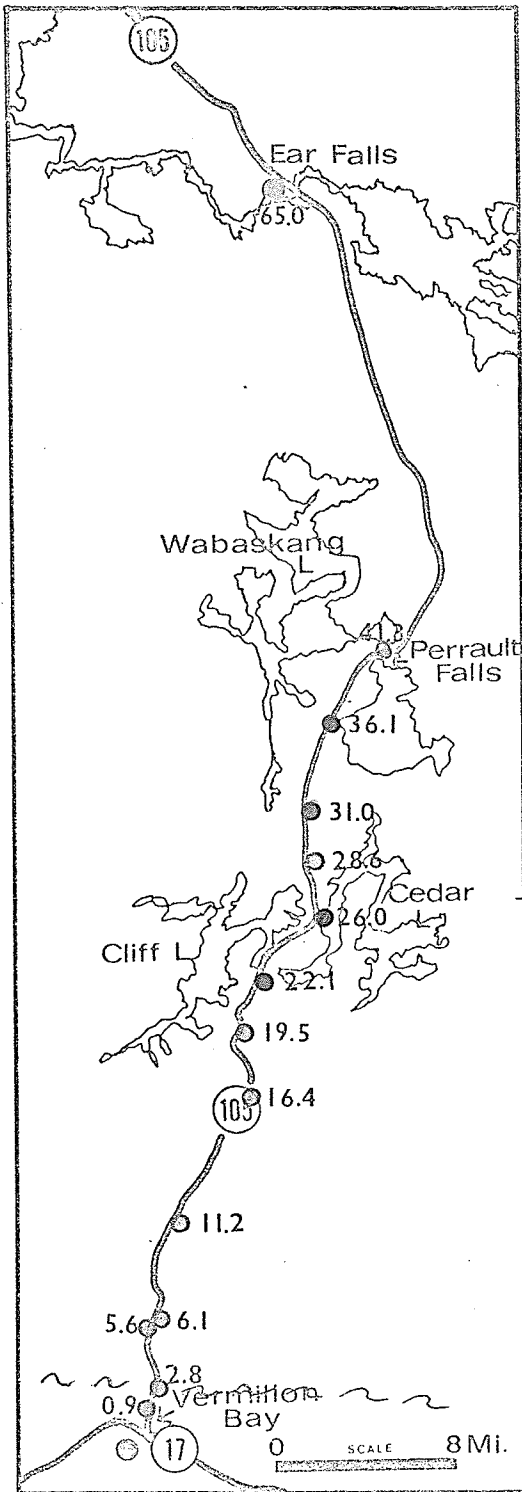


FIGURE 22 - Map showing the metamorphic zones with sample locations plotted.

- Represents the upper-amphibolite facies.
- Represents the hornblende-clinopyroxene-plagioclase subfacies.
- Represents the hornblende-orthopyroxene-plagioclase subfacies.

hornblende may not have been able to leave the relatively closed system. Thus most of the hornblende was preserved because of the increase in PH_2O . On the contrary, in the pyroxene granulite which is metasedimentary in origin and contains only 1 per cent hornblende, the water content was either initially very low or may have been lost during a crest of high grade metamorphism, and little hornblende was formed.

Compositions of the metasedimentary rocks along the Red Lake road indicate that they were initially greywackes and shales. The original compositions of the metasediments undisturbed by anatexis and metasomatic processes appears to be preserved only locally. Most of the metasediments have been partially melted and transformed into migmatites and granitoid rocks.

The compositions of the metasediments within the English River belt are similar to those within the greenstone belt. The only compositional difference is that the iron of the greenstone metasediments is more reduced. Mineralogically the differences between the two groups are in amounts of minerals, not in species.

Trends in amphibolite compositions indicate that they are igneous in origin. The amphibolites within the

greenstone belt are late stage basic igneous rocks and the amphibolites within the English River belt are middle to late stage igneous rocks. Mineralogically and texturally the greenstone amphibolites differ from those within the English River gneissic belt. The English River belt amphibolites were possibly originally basic sills and dykes, which were subjected to high grade regional metamorphism. This would account for their limited extent and sharp contacts with the granitic rocks in the English River belt. The greenstone amphibolites are more typical metavolcanic rocks associated with volcanic belts.

The relationship between other structures of the belt and the pressure temperature gradients as interpreted from this study of the metamorphism, indicate that there is no coincidence between metamorphic grade and the southern fault boundary. There is no sudden increase in metamorphic grade across the fault boundary into the English River gneissic belt. Only in the central portion of the belt are rocks of the granulite facies present. Therefore, the faulting is related to a later process than that of the metamorphism. The high grade regional metamorphism in the English River belt does not seem to be the result of uplift and subsequent exposure of rocks of deep crustal origin. The fact that there is a thick upper crust and a thin lower crust below the belt contradicts a differential uplift process. If uplift had occurred

the upper crust would be thinner than that under the greenstone belt to the north and south. However, this is not the case. Results of seismic work infer that the crust beneath the belt has been stretched in a north-south direction producing a typical rift structure. Sometime during the evolution of the Superior Province processes must have been active which resulted in large temperature-pressure gradients. The geosynclinal environment of the English River belt was then subjected locally to high temperatures and pressures. The fault zones which border the English River gneisses do not necessarily indicate uplift of the belt. They could have resulted from the deformation which stretched the crust below the English River gneisses.

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APPENDIX I

Chemical Composition of Rocks

A. Metasedimentary Rocks

| <u>Sample No.</u> | <u>J0.9B</u> | <u>J0.9D</u> | <u>J2.1D</u> | <u>J2.6C</u> | <u>J2.8A</u> | <u>J19.5A</u> | <u>J28.6B</u> | <u>J65A</u> | <u>J65B</u> | <u>J65E</u> | <u>J65O</u> | <u>J65T</u> | <u>J65X</u> |
|---|--------------|--------------|--------------|--------------|--------------|---------------|---------------|-------------|-------------|-------------|-------------|-------------|-------------|
| SiO ₂ | 58.65 | 59.50 | 70.10 | 61.10 | 61.95 | 66.90 | 67.95 | 59.90 | 68.45 | 55.60 | 55.45 | 70.90 | 70.15 |
| Al ₂ O ₃ | 18.69 | 17.84 | 13.03 | 16.65 | 16.48 | 14.88 | 15.04 | 17.74 | 14.23 | 19.20 | 18.42 | 13.42 | 13.68 |
| Fe ₂ O ₃ | 1.30 | 0.87 | 1.01 | 1.45 | 2.64 | 2.13 | 1.55 | 1.11 | 1.01 | 1.29 | 1.31 | 0.25 | 0.66 |
| FeO | 6.12 | 6.12 | 4.24 | 4.20 | 3.16 | 3.32 | 2.40 | 5.76 | 4.44 | 8.72 | 7.92 | 3.44 | 3.24 |
| MgO | 3.45 | 3.54 | 2.75 | 3.35 | 1.95 | 1.02 | 1.10 | 2.90 | 2.28 | 6.03 | 3.80 | 1.90 | 2.40 |
| CaO | 2.53 | 1.78 | 1.99 | 5.54 | 4.57 | 2.94 | 3.48 | 2.66 | 2.42 | 1.07 | 2.21 | 2.49 | 2.16 |
| Na ₂ O | 3.34 | 3.30 | 2.40 | 3.56 | 4.40 | 3.62 | 4.60 | 4.06 | 3.17 | 0.95 | 3.00 | 3.60 | 3.32 |
| K ₂ O | 2.82 | 4.11 | 2.40 | 1.57 | 2.13 | 2.37 | 1.68 | 2.63 | 1.78 | 3.02 | 2.08 | 1.72 | 2.25 |
| H ₂ O ⁺ H ₂ O ⁻ H ₂ O | 1.78 | 1.830 | 1.335 | 1.230 | 0.840 | 0.605 | 0.700 | 1.775 | 1.12 | 2.35 | 3.745 | 0.930 | 1.230 |
| CO ₂ | 0.22 | 0.110 | 0.080 | 0.310 | 0.055 | 0.125 | 0.160 | 0.035 | 0.37 | 0.46 | 0.055 | 0.020 | 0.015 |
| TiO ₂ | 0.66 | 0.68 | 0.29 | 0.45 | 0.78 | 0.62 | 0.51 | 0.77 | 0.42 | 0.74 | 0.83 | 0.42 | 0.015 |
| P ₂ O ₅ | 0.13 | 0.33 | 0.13 | 0.19 | 0.33 | 0.28 | 0.24 | 0.16 | 0.11 | 0.11 | 0.24 | 0.22 | 0.16 |
| MnO | 0.08 | 0.086 | 0.079 | 0.103 | 0.116 | 0.130 | 0.078 | 0.080 | 0.09 | 0.14 | 0.122 | 0.080 | 0.100 |
| Total | 99.77 | 100.10 | 99.83 | 99.67 | 99.40 | 98.94 | 99.49 | 99.57 | 99.89 | 99.68 | 99.27 | 99.39 | 99.82 |

B. Amphibolites

C. Granitic Rocks

| <u>Sample No.</u> | <u>J2.6D</u> | <u>J2.6F</u> | <u>J2.6G</u> | <u>J11.2</u> | <u>J22.1</u> | <u>J28.6D</u> | <u>J31B</u> | <u>J36.1</u> | <u>J2.8B</u> | <u>J2.8C</u> | <u>J2.8F</u> | <u>J28.6A</u> |
|--------------------------------|--------------|--------------|--------------|--------------|--------------|---------------|-------------|--------------|--------------|--------------|--------------|---------------|
| SiO ₂ | 46.35 | 49.65 | 44.95 | 53.50 | 48.40 | 46.05 | 47.30 | 52.15 | 65.35 | 73.15 | 75.25 | 71.90 |
| Al ₂ O ₃ | 12.69 | 14.33 | 13.63 | 13.04 | 13.02 | 14.16 | 14.10 | 13.98 | 16.60 | 14.78 | 13.96 | 14.93 |
| Fe ₂ O ₃ | 3.77 | 2.85 | 3.15 | 3.12 | 3.04 | 3.80 | 3.82 | 2.58 | 1.40 | 0.21 | 0.14 | 0.01 |
| FeO | 13.36 | 11.36 | 15.08 | 6.16 | 9.36 | 8.20 | 8.40 | 11.84 | 2.40 | 0.60 | 0.84 | 0.72 |
| MgO | 5.75 | 4.60 | 5.07 | 7.80 | 8.13 | 9.00 | 9.15 | 3.25 | 1.95 | 0.31 | 0.21 | 0.28 |
| CaO | 10.22 | 9.17 | 9.85 | 8.69 | 12.04 | 11.84 | 11.06 | 8.62 | 4.36 | 1.40 | 0.48 | 1.63 |
| Na ₂ O | 2.78 | 3.38 | 2.78 | 3.40 | 2.70 | 2.96 | 2.71 | 2.95 | 4.02 | 3.90 | 3.08 | 3.68 |
| K ₂ O | 0.40 | 0.33 | 0.46 | 1.02 | 0.62 | 0.78 | 0.74 | 0.43 | 1.79 | 4.37 | 5.46 | 5.69 |
| H ₂ O | 1.44 | 1.13 | 1.635 | 1.54 | 0.94 | 1.400 | 1.50 | 1.14 | 0.870 | 0.62 | 0.60 | 0.505 |
| CO ₂ | 0.11 | 0.18 | 0.315 | 0.26 | 0.13 | 0.080 | 0.16 | 0.22 | 0.035 | 0.19 | 0.09 | 0.175 |
| TiO ₂ | 2.28 | 1.94 | 2.07 | 0.63 | 0.77 | 0.80 | 0.60 | 1.87 | 0.50 | 0.04 | 0.01 | 0.10 |
| P ₂ O ₅ | 0.19 | 0.24 | 0.61 | 0.22 | 0.13 | 0.15 | 0.11 | 0.21 | 0.23 | 0.07 | 0.07 | 0.07 |
| MnO | 0.24 | 0.22 | 0.510 | 0.16 | 0.20 | 0.282 | 0.19 | 0.32 | 0.062 | 0.025 | 0.093 | 0.036 |
| Total | 99.58 | 99.38 | 100.00 | 99.54 | 99.48 | 98.90 | 99.84 | 99.56 | 99.56 | 99.66 | 100.19 | 99.74 |

APPENDIX II

Anorthite Contents of Plagioclases

A. Metasedimentary Rocks

| <u>Sample No.</u> | <u>An Percent</u> |
|-------------------|-------------------|
| J0.9B | 31 |
| J2.8A | 30 |
| J16.4 | 29 |
| J19.5C | 31 |
| J26.0 | 66 |
| J28.6B | 36 |
| J65B | 32 |
| J65C | 31 |
| J65D | 31 |
| J65E | 30 |
| J650 | 30 |
| J65X | 32 |

B. Amphibolites

| <u>Sample No.</u> | <u>An Percent</u> |
|-------------------|-------------------|
| J2.6D | 39 |
| J2.6F | 37 |
| J11.2 | 36 |
| J22.1 | 52 |
| J28.6 | 44 |
| J31B | 48 |
| J36.1 | 48 |