ELEMENT DISTRIBUTION IN COEXISTING PYROXENES FROM GRANULITE ROCKS OF SOUTHEAST STANWELL-FLETCHER LAKE AREA, SOMERSET ISLAND, DISTRICT OF FRANKLIN, N.W.T.

By

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ABSTRACT

Part I: The area studied is situated on Somerset Island, District of Franklin, N.W.T.

Most of the rocks in this area are Proterozoic metamorphics of granulite facies. It is suggested that these rocks were formed as the result of relatively high temperature and water pressure, and low confining pressure for the granulite facies.

Part II: The distribution of magnesium, bivalent and trivalent iron, manganese, titanium and calcium between coexisting orthopyroxene and calcic pyroxene in the granulite rocks was studied.

From the shape of the best fit coefficient of distribution curve with respect to magnesium and bivalent iron, it is concluded that the distribution of these ions in orthopyroxene is not ideal.

The coefficient of distribution of manganese with respect to magnesium and bivalent iron was found to decrease towards unity, that is, approach ideality with increasing temperature.

It is suggested that an exchange equilibrium exists between trivalent iron and titanium, provided that titanium is assumed to be trivalent.

Calcium is not involved in an exchange equilibrium in coexisting pyroxenes.

A tentative geothermometer is proposed on the basis of the coefficient of distribution of magnesium with respect to bivalent iron, and of the coefficient of distribution of manganese with respect to magnesium and bivalent iron. From this geothermometer, a range of temperatures and pressures for published pyroxene pair analyses in granulitic rocks is established. The temperatures and pressures range approximately between 680° C with a pressure of 5200 Atm and 760° C with pressure of 3000 Atm.

With this geothermometer, the values for the rocks from the Stanwell-Fletcher Lake area are 785° C with corresponding pressure of 3,050 Atm.

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INTRODUCTION

The area covered by this thesis is situated on the central portion of Somerset Island.

More precisely the area concerned in this work is situated between the south-eastern end of Stanwell-Fletcher Lake and the westernmost part of Creswell Bay. It is geographically bounded by latitude 72° 41' N and 72° 49' N and longitudes 94° 05' W and 94° 39' W. The area has been mapped at one-half mile to the inch scale, and covers approximately 50 square miles. It is known as the Union River area.

Access to the area is by aircraft, Nordair Aviation, Limited which has weekly flights from Montreal, Quebec, to Resolute Bay, District of Franklin. From there chartered light aircraft provides transportation for the final 134 miles to the base camp, which was situated on the eastern shore of Stanwell-Fletcher Lake, opposite the southernmost and the largest island in that Lake (Figure 1).

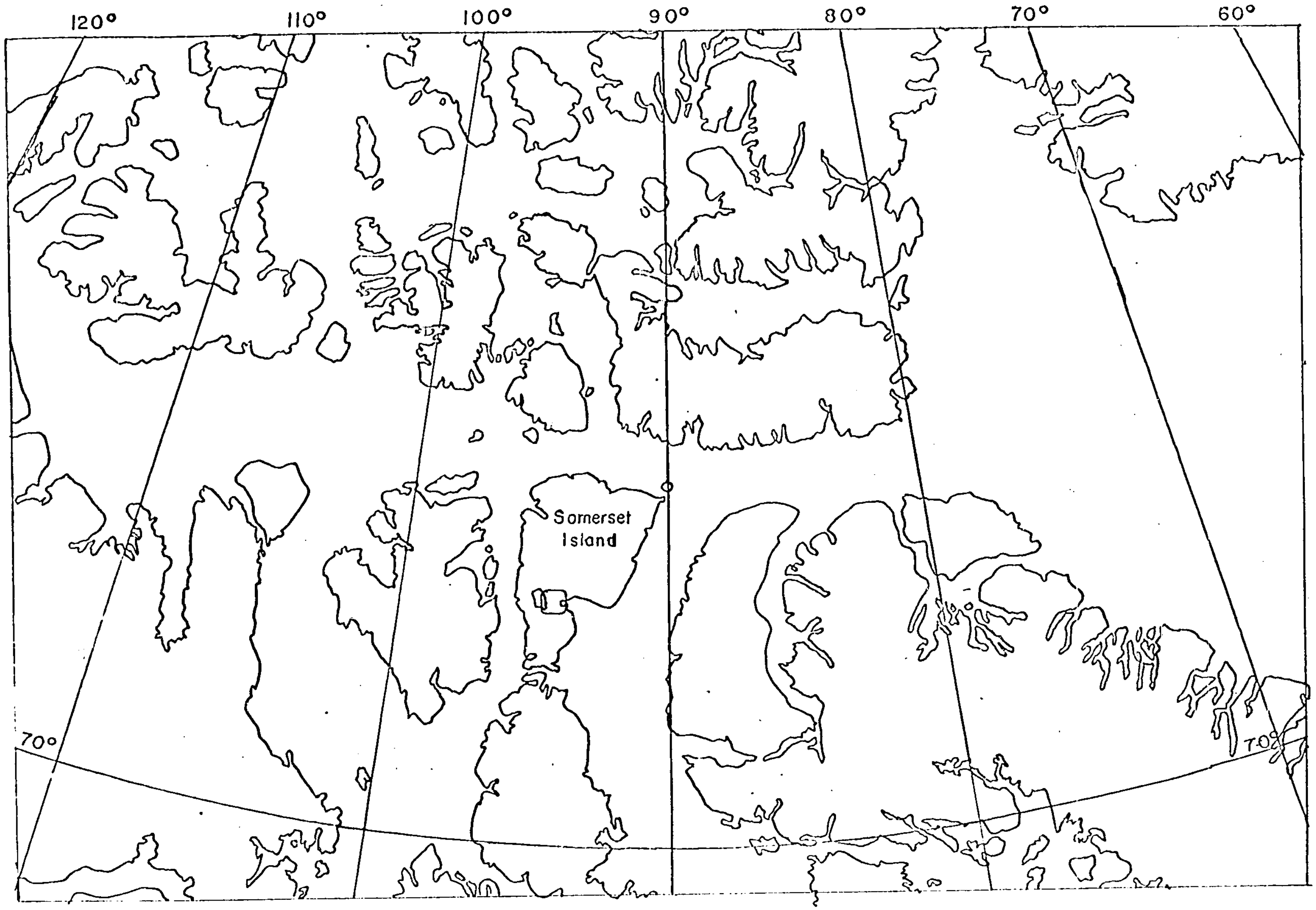

Figure 1: Area mapped is located by the red square on Somerset Island.

ACKNOWLEDGEMENTS

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A final thanks is extended to Mrs. G. Nivins who typed this thesis.

PART I

REGIONAL GEOLOGY

PREVIOUS WORK ON THE REGIONAL GEOLOGY

In the early days of arctic exploration, the purpose of many expeditions was the discovery of the Northwest Passage. Any scientific observations made during these expeditions were of a secondary interest.

Somerset Island was discovered by Parry during his first voyage to the arctic in 1819-20. Later, in 1822-25 he followed the east coast of Somerset Island and noted that the cliffs on the west coast of Prince Regent Inlet were predominantly limestone with beds of gypsum (Appendix 3rd voyage).

Sir John Ross (1829-33) noted limestone at Cape Gary (p.112), and both limestone and granite near Possession Point (p.116), where the contact between the Precambrian and the Paleozoic is exposed.

A party led by James C. Ross, including F.L. McLintock, explored the east, north and west coasts of Somerset Island, noting the presence of "granite" on the west coast (McLintock, 1857).

Further work of geological interest was the description of fossils by A.E. Wilson (1939, 1949 and 1952), based on collections made by Nichols, Learmouth and Shudman respectively.

Fortier (1948) made an aircraft survey and noted the presence of crystalline rocks on the western portion of the island. Operation Franklin, carried out in 1955, outlined the main geological boundaries (Fortier et al, 1963). The arching character of the geological features was previously established from the study of the Cornwallis fold belt (Fortier et al, 1954).

Blackadar (Blackadar and Christie 1963, Blackadar, 1967) who carried out field work in 1963, subdivided the Precambrian into seven major rock types, three of which apply to the area mapped by the author. These rock types are: biotite-hornblende gneiss; quartz-feldspar gneiss and gabbro.

Expeditions led by Dr. D. L. Dineley of the University of Ottawa, began geological field work in 1964 and continued in 1965.

This work is part of the 1965 expedition.

GENERAL GEOLOGY

All consolidated rocks in this map area can be subdivided into 3 distinctive types:

1) Paleozoic rocks.
2) Proterozoic intrusive rocks.
3) Proterozoic metamorphic rocks.

Paleozoic Rocks: (8)[1]

Paleozoic rocks, which are assigned to the Cambrian by Christie (Blackadar and Christie, 1963) on the basis of fossils identified by A. W. Norris, collected near Kangikjuke Lake, Lower Boothia Peninsula, are located on the east edge of the map area. Along the north shore of Creswell Bay, these rocks unconformably overlie the Precambrian. The unconformity does not appear to be a faulted boundary, though evidence of strike slip movement (slickensides) in the underlying Precambrian rocks was noted.

The Cambrian rocks at this point are approximately 150 feet thick and are composed at the base of a poorly consolidated, medium-grained, white cross-bedded orthoquartzite. The remainder of the unit is composed of shaly dolomite, stromatolitic dolomite, intraformational conglomerate, and massive "lithographic" dolomite.

Other Paleozoic rocks were noted on the islands in Creswell Bay, and on the south shore of the Bay. These rocks are also assigned to the Cambrian (Blackadar and Christie, 1963), though they were not studied by the author.

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[1] Numbers in parenthesis refer to map units.

The only other unmetamorphosed sedimentary rocks classed as ?Paleozoic noted in the area occur as an outlier in the north-west portion of the map area. This rock is a silty dolarenite of light buff colour. Very little rock is in place and the age of the outlier is uncertain.

?Proterozoic Intrusive Rocks: (7)

Basic rocks thought to be late Proterozoic or early Paleozoic (Blackadar and Christie, 1963) are found in the form of dykes and as a small pipe in this map area.

The dykes are of 3 types, and are subdivided as follows:

7) Diabase (ophitic variety of gabbro) (10^t)*
7a) Diorite (5^t)
7b) Pigeonite gabbro (northern-most dyke near Stanwell-Fletcher Lake) (1^t)

The dykes as a rule are parallel to lineaments and are thought to occupy structurally weak zones. Two trends are distinctive. Those following an east-west alignment tend to have a width of about 10 to 20 feet, and those bearing N35°W average in width around 200 feet. The composition of the dykes cannot be related to their trends in an area of this size.

A small circular diorite body was located in the north-west section of the map area. The diameter of this body is 70' and it is thought to be a small pipe.

The basic intrusive rocks weather moderate reddish brown and are generally well jointed parallel or at 90° to

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* Note - number in bracket with 't' suffix indicates the number of thin section for that assemblage.

the dyke wall.

Contact effects are limited to a narrow chilled margin within the intrusion, though no glass was noted. The country rock is unaffected.

PROTEROZOIC METAMORPHIC ROCKS

The metamorphic rocks of Somerset Island were formerly thought to be Archean in age, (Blackadar and Christie, 1963) but potassium argon dating on biotite has shown them to be Proterozoic.

Ages obtained on Somerset Island and on the Boothia Peninsula are as follows:

A) Somerset Island: 72° 38' N, 94° 28' W.

Age: 1,670 ± 50 M.Y.

Rock: Biotite-hypersthene-quartz-microcline-plagioclase gneiss.

Reference: Wanless et al 1965, p. 24.

Note: This place is located 7.2 miles from the mouth of the Union River on a bearing of 228°.

B) Boothia Peninsula, 71° 18' N, 95° 55' W.

Age: 1,635 ± 50 M.Y.

Rock: Biotite-hornblende-pyroxene-quartz-microcline-plagioclase gneiss.

Reference: Wanless et al, 1965, p. 24.

Pegmatite (6)

Coarse pegmatite occurs as lenses in various gneisses. These lenses are parallel to foliation trends. Since large granite bodies are absent in the area, the pegmatite lenses are probably the result of localized melting during metamorphism and are therefore classed as metamorphic rocks.

The next five units are gneisses, which are considered by Blackadar (1967) to be of sedimentary and volcanic origin.

According to Blackadar (1967):

> "Evidence for the non-igneous origin of much of the gneissic complex is widespread. The presence of bands of crystalline limestone interbedded with the gneisses near Bellot Strait suggests a sedimentary origin for both the enclosing gneisses and the carbonate bands. Similarly, many of the leucocratic gneisses contain abundant plagioclase and quartz, and some still exhibit gradation between coarse and fine-grained layers. Such rocks may be metamorphosed arkose. Many melanocratic gneisses may be derived by metamorphism of argillaceous sedimentary rocks, but others

are obviously of volcanic or igneous origin.....

Amphibolite bands, present in both map-units 1 and 2 (G.S.C. Maps P.S. 3-1967), may locally form up to 20 per cent of the rock. They may be derived from marly or calcareous sedimentary rocks, basic or ultrabasic intrusive rocks, or volcanic rocks. In Boothia-Somerset map-area no relic textural features were found that could establish their original nature."

Subdivision of the 2 units in the area studied here is mainly on the basis of physical field characteristics, such as colour index, main rock forming minerals, banding, continuity of the units, a feature usually visible on aerial photographs and weathering properties.

Banded Quartz-feldspar gneiss (5)

This unit corresponds in part to Blackadar's unit 2. The rocks as mapped by the author are essentially a banded gneiss complex in which units vary from 2 inches to 15 feet in width. These rocks are characterized by the presence of biotite quartz and potassium feldspar. Within this unit are several sub-units of which one key unit in the easternmost part of the map area is composed of a quartz-microcline-plagioclase-garnet-sillimanite assemblage. Sillimanite is a very minor constituent. The presence of sillimanite and kyanite in this unit tends to favour a sedimentary origin for these rocks, though a volcanic origin cannot be ruled out.

A summary of assemblages encountered in this unit is listed below. All are reported by Blackadar (1967) as being in his unit 2, except for assemblages 5 and 6.

1. Quartz-microcline-plagioclase-biotite-garnet. (2^{t})
2. Quartz-microcline-plagioclase-biotite-clinopyroxene. (2^{t})
3. Quartz-microcline-plagioclase-biotite-hornblende-orthopyroxene. (1^{t})
4. Quartz-microcline-plagioclase-biotite-orthopyroxene-clinopyroxene. (4^{t})

Also assigned to this unit are those felsic rocks that have over 50 per cent quartz content. These rocks are not biotite bearing assemblages, but are physically associated with them.

5. Quartz-microcline-plagioclase-orthopyroxene-clinopyroxene-kyanite. (1^{t})
6. Quartz-microcline-plagioclase-garnet-sillimanite. (1^{t})
7. Quartz-microcline-plagioclase-orthopyroxene-garnet. (3^{t})

The garnets have a refractive index of 1.716, which is slightly higher than the value for pyropes. They are, therefore, thought to be near the pyrope end member in the pyrope-almandine series, although refractive index values are not conclusive for garnet identification. The colour of the garnets varies from red to black in hand-specimen. Pyrope garnets have been reported in metamorphic rocks from other granulite areas (Wilson, A. F., 1959).

Of the specimens studied in part II, numbers 8, 34 and 36 come from this unit.

Migmatites (4)

The rocks are predominantly "lit par lit" migmatites made up of narrow bands, varying between 2 and 6 inches thick. The felsic component comprising assemblages 1 and 4 are interbanded with mafic assemblages 2, 3 and 5.

The mafic members comprise approximately 40 per cent of the unit. The felsic members are gneissic and fine-grained, showing igneous texture only locally. This leads the author to believe that the banding is primarily a sedimentary feature. The following assemblages were noted:

1. Quartz-microcline-plagioclase. (3^t)
2. Quartz-plagioclase-(orthopyroxene and/or clinopyroxene). (5^t)
3. Quartz-microcline-plagioclase-hornblende. (2^t)
4. Quartz-microcline-plagioclase-biotite. (1^t)
5. Microcline-plagioclase-orthopyroxene-clinopyroxene-hornblende-biotite. (1^t)

Of the specimens studied in Part II, specimen #56 comes from this unit.

Gneisses: High Content of Mafic Minerals (3)

These are melanocratic gneissic rocks almost approaching basalt in composition and are most probably metavolcanic.

This may be one of the "sills" reported by Blackadar, (1963) but because of the persistent thickness of the unit within the map area, the author tends to classify it as a volcanic. This rock has relic igneous texture in some specimens which could be preserved during regional metamorphism. The pyroxenes from this unit, as seen in part II, are apparently in equilibrium with the other specimens from the region. The possibility that this rock type, where located, could be a sill, cannot be overlooked.

Assemblages noted from this unit:

1. Plagioclase-orthopyroxene-clinopyroxene-hornblende and/or biotite. (3^t)
2. Plagioclase-clinopyroxene-hornblende and/or biotite. (6^t)
3. Plagioclase-orthopyroxene-hornblende. (1^t)
4. Plagioclase-orthopyroxene-clinopyroxene. (1^t)
5. Plagioclase-orthopyroxene-biotite-garnet-sapphirine. (1^t)

Sapphirine was identified in only one specimen. It is a characteristic but rare mineral of the upper granulite facies. Positive identification was by X-Ray, table #1, and can be seen as the dark blue mineral in plate 1.

Of the specimens studied in Part II, number 94 comes from this unit.

Mafic gneisses; intermediate content of mafic minerals: (2)

These rocks are very similar to unit 3, but have a stronger predominance of felsic material, that is, they are approaching the composition of andesite. The assemblages assigned to this unit are as follows:

1. Plagioclase-orthopyroxene-clinopyroxene (biotite). (3^{t})
2. Plagioclase-orthopyroxene-clinopyroxene. (1^{t})

Layered gneissic quartz diorite: (1)

These rocks are quartz diorite in composition, strongly gneissic with very little banding. These rocks would be included in Blackadar's unit 1 and are very widespread. It was not possible to determine whether these rocks are sedimentary or volcanic in origin. These rocks can be mapped as a unit. The beds within the unit vary between 1 and 10 feet in thickness.

The assemblages found are as follows:

1. Quartz-plagioclase-orthopyroxene-biotite. (2^{t})
2. Quartz-plagioclase-clinopyroxene-hornblende. (3^{t})
3. Quartz-plagioclase-orthopyroxene-clinopyroxene
   (biotite and/or hornblende). (5^{t})
4. Quartz-plagioclase-orthopyroxene-clinopyroxene. (5^{t})

Of the specimens studied in part II, number 1 comes from this unit.

STRUCTURAL GEOLOGY

The area is cut by many topographic lineaments which control the drainage pattern of the area.

A fault extends along the north shore of Creswell Bay, then across the map area in an east-west direction, leaving land near the north end of the main island in Stanwell-Fletcher Lake. This fault has as topographic expression a scarp which extends the full length of the area. The north side of the scarp is approximately 1000 feet higher than the southern side. In the rocks along this fault, there is commonly evidence of retrograde metamorphism marked by the presence of epidote. There is a rock type change across this east-west fault in the westernmost end. The extent of the movement was not determined.

A small branch fault, with sinistral offset was noted on the north side of the scarp near the easternmost large inland lake. The approximate bearing is N 45° W, and horizontal offset of steeply dipping layers was measured at 200 feet along this fault.

In the central portion of the area where the foliation has a strike near 00° with a dip near vertical, the rock units have a deflection in the trend which suggest dextral movement along the east-west bearing fault.

A second major fault was traced along a bearing of N 30° W and is marked by topographic depression. This fault has a change in rock type across it. The trend of this fault parallels the east and west boundaries of Stanwell-Fletcher Lake. This fault is also paralleled by two basic dykes.

The foliation, determined by gneissic layering of hornblende and biotite, is on a bearing of N 30° W in the western sector of the map area changing to due north in the eastern sector across the above mentioned N 30° W bearing fault.

Minor folds were noted in a few localities but were too few in numbers to be significant.

One large fold was noted near the eastern boundary in the northeast corner of the map area. The full extent can be traced by aerial photographs.

Several lineaments parallel the east-west fault though no apparent movement is noted. The Union River is controlled by the presence of one of these lineaments.

A second main lineament trend has a bearing of N 30° W and is parallel to Stanwell-Fletcher Lake. This is parallel to what is thought to be a downfault block which is occupied by the Lake (Dineley 1965).

CONCLUSION

From the study of this area, there is no apparent basis for the subdivision of this area of the granulite facies into a lower and higher temperature group on the basis of the presence or absence of hornblende and/or biotite (Turner and Verhoogen 1961). Pyroxene granulite assemblages are interbedded with hornblende amphibolite facies rock.

De Waard (1963) outlined a new subdivision of the granulite facies. De Waard's (1963) classification is six fold. It is subdivided into 3 groups, each made up of a subfacies with hydrous minerals, such as biotite and hornblende, and one without hydrous minerals.

The lowest pair is characterized by the presence of cordierite. The second pair is characterized by the presence of orthopyroxene and plagioclase. The third pair is characterized by a clinopyroxene-almandine association.

From the assemblages studied in this work, the existence of a cordierite isograd appears likely. The presence or absence of hydrous minerals is probably dependent on the porosity and permeability of the original rocks as hydrous and anhydrous assemblages coexist.

The coexistence of the various other subfacies lends doubt as to the existence of de Waard's garnet isograd.

From the tentative temperature and pressure defined in part II of this work, and the presence of hydrous mineral assemblages, the rocks studied in this thesis originated under high temperature, relatively low pressure for granulite facies rocks and under relatively high water pressure.

PART II

ELEMENT DISTRIBUTION

IN COEXISTING PYROXENES

FOREWORD

The notations used herein are as follows:

G: Gibbs free energy
μE: excess chemical potential
T: absolute temperature
P: pressure
H: enthalpy
V: volume
R: gas constant
X: mole fraction
xy: mole position in unit cell
K_D: distribution coefficient
ss: solid solution
μ_i: chemical potential of a component i
n_i: number of moles of i in a system

Chemical formulas that form subscripts to G, H, and V refer to phases, and those which form subscripts to X and μ^E refer to components of solid solutions. Fe and Mn refer to bivalent iron and manganese unless otherwise indicated.

Data calculations, with the exceptions of those involving distribution coefficients with reference to trivalent titanium and iron, were performed by an IBM System 360 digital computer programmed by Mrs. A. Hurd of the University of Ottawa Computing Center.

PURPOSE OF WORK

The rocks under study are confined to a section bordering the south-east and south-west end of Stanwell-Fletcher Lake on Somerset Island, N.W.T. (fig. 2). All rocks within this area are assigned to the granulite facies and have evidently originated under uniform temperature and pressure conditions.

Several of the various granulitic rocks contain co-existing orthopyroxene and monoclinic calcic pyroxene.

The object of this work is to investigate the distribution of bivalent Iron (Fe), Magnesium (Mg), Manganese (Mn), Trivalent Iron (Fe^{+3}), Titanium (Ti) and Calcium (Ca) between these two minerals, and to consider the termodynamic factors which control this distribution.

PREVIOUS WORK

Hess (1941) investigated minerals from the Stillwater complex and suggested that the projection of the tie line between two coexisting pyroxenes in the system $MgSiO_3$ - $CaSiO_3$ - $FeSiO_3$ would intersect the $MgSiO_3$ join at a fixed point.

Later Wilson (1960) further suggested that this point of intersection would vary according to temperature of origin of the pyroxene pairs. This direction of investigation ceased following its rejection by Kretz (1961) and Bartholomé (1961).

Mueller (1960) presented the first thermodynamic analysis of compositional data for coexisting calcic pyroxene and orthopyroxenes in metamorphic rocks. He showed that when the distribution of Mg and Fe^{+2} between orthopyroxenes and calcic pyroxenes is expressed in the form of the Mass Action Law, (1) it reveals a close approach to equilibrium with reference to the (Mg-Fe^{+2}) exchange and it also provided indication that both phases behave according to the model of an ideal mixture.

Kretz (1961) and Bartholome (1961) independently observed that the distribution coefficient of the (Mg-Fe^{+2}) exchange for coexisting calcic pyroxene and orthopyroxene (or pigeonite) was displaced towards unity in the case of rocks of known or presumed igneous crystallization.

Kretz (1961) outlined the exchange equilibrium for the minor element, Mn, between orthopyroxene and clinopyroxene, and showed that, provided X_{MnSiO_3} and $X_{MnCaSi_2O_6}$ are sufficiently low to satisfy Henry's law, the distribution coefficient of (Mn-Mg, Fe) is a function only of temperature, pressure and the Mg:Fe ratio in one phase, say, orthopyroxene. Furthermore, Kretz constructed a tentative equilibrium diagram relating the distribution coefficient with reference to coexisting pyroxene phase $K_D(Mg-Fe^{+2})$, absolute temperature (T), and pressure in atmospheres (P). This construction is based on published empirical data. This diagram unfortunately gives an infinity of possibilities of temperature and pressure for any given distribution coefficient of $(Mg-Fe^{+2})$.

This thesis continues on the basis of Kretz' work.

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(1) Mass Action Law: The equilibrium between substances proportional to the active concentrations of the reacting substances, each raised to the power numerically equal to the number of molecules appearing in the balanced equation.

OUTLINE OF THE PROBLEM

A metamorphic rock may be considered as a thermodynamic system. Within this system certain main thermodynamic properties may be defined. There are properties which depend upon the quantity of the system such as entropy (S), volume (V), the number of moles of any component (n_i). These are known as extensive properties. Other properties, independent of the quantity of the system, such as pressure (P), absolute temperature (T) and the chemical potential of a component are known as intensive properties.

At equilibrium all elements are distributed between the different phases in accordance with the different thermodynamic properties. If any intensive property changes, that is, a new equilibrium is coestablished, the distribution of elements between coexisting minerals (phases) in the same system will be different.

In a multiphase equilibrium the distribution of a component may be represented by a bundle of tie-lines in a phase diagram or by a term known as a co-efficient of distributions (K_D). The limiting case is a system which is univariant at constant pressure (or temperature). The composition of the phases is then determined at specified temperature (or pressure).

The distribution co-efficient can be shown by thermodynamic considerations to be dependent upon temperature, pressure, and the concentration of a third component in either phase.

The expressions for effect of temperature and pressure were developed by Ramberg (1952) and the expression for the influence of the concentration of a third species within either phase was developed by Kretz (1961).

The study of coexisting pyroxenes in metamorphic rocks presents naturally occurring test for the validity of the theoretical expectations. This type of study also provides an insight into the conditions for formation of these metamorphic rocks.

CHOICE OF SPECIMENS

In choosing specimens for study three things were considered:

A) All specimens must be in local equilibrium, that is, there must be no evidence of alteration of the rock to a different facies than that at which the rock formed.

B) The pyroxene within a rock must show some evidence of being in stable coexistence; the physical contact of the orthopyroxene with calcic pyroxene without chemical reaction is acceptable evidence.

C) Rocks must be fresh, that is, they must show little or no weathering characteristics.

In the description of the seven chosen specimens, the following rules were followed:

1) All modal quantities were determined by point counter.

2) In studying the pyroxenes and the feldspars, the angle between the isogyres of the biaxial interference figures were measured on a Leitz Universal Stage.

Separation and analytical techniques are outlined in the Appendix.

These are the seven assemblages from which the pyroxenes were chosen for detailed study.

(1) Quartz-plagioclase-calcic pyroxene-orthopyroxene.

(8) Quartz-plagioclase-orthopyroxene-calcic pyroxene-hornblende-biotite-magnetite-apatite.

(34) Quartz-plagioclase-orthopyroxene-calcic pyroxene-hornblende-magnetite.

(36) Plagioclase-orthopyroxene-calcic pyroxene-biotite-magnetite-apatite.

(56) Plagioclase-orthopyroxene-calcic pyroxene-biotite-magnetite-apatite.

(94) K-spar-plagioclase-hornblende-orthopyroxene-calcic pyroxene-magnetite.

(125) Plagioclase-orthopyroxene-calcic pyroxene-magnetite-apatite.

A detailed study of each specimen is in the appendix.

Each specimen is plotted on the lower half of the diagram representing the $CaSiO_3$ - $FeSiO_3$ - $MgSiO_3$ system. Figure 3 shows pyroxene pairs plotted as analysed. As only the tie line of sample #1 crosses other tie lines, and at a small angle, it can be assumed that all the rocks originated near the same temperature and pressure conditions.

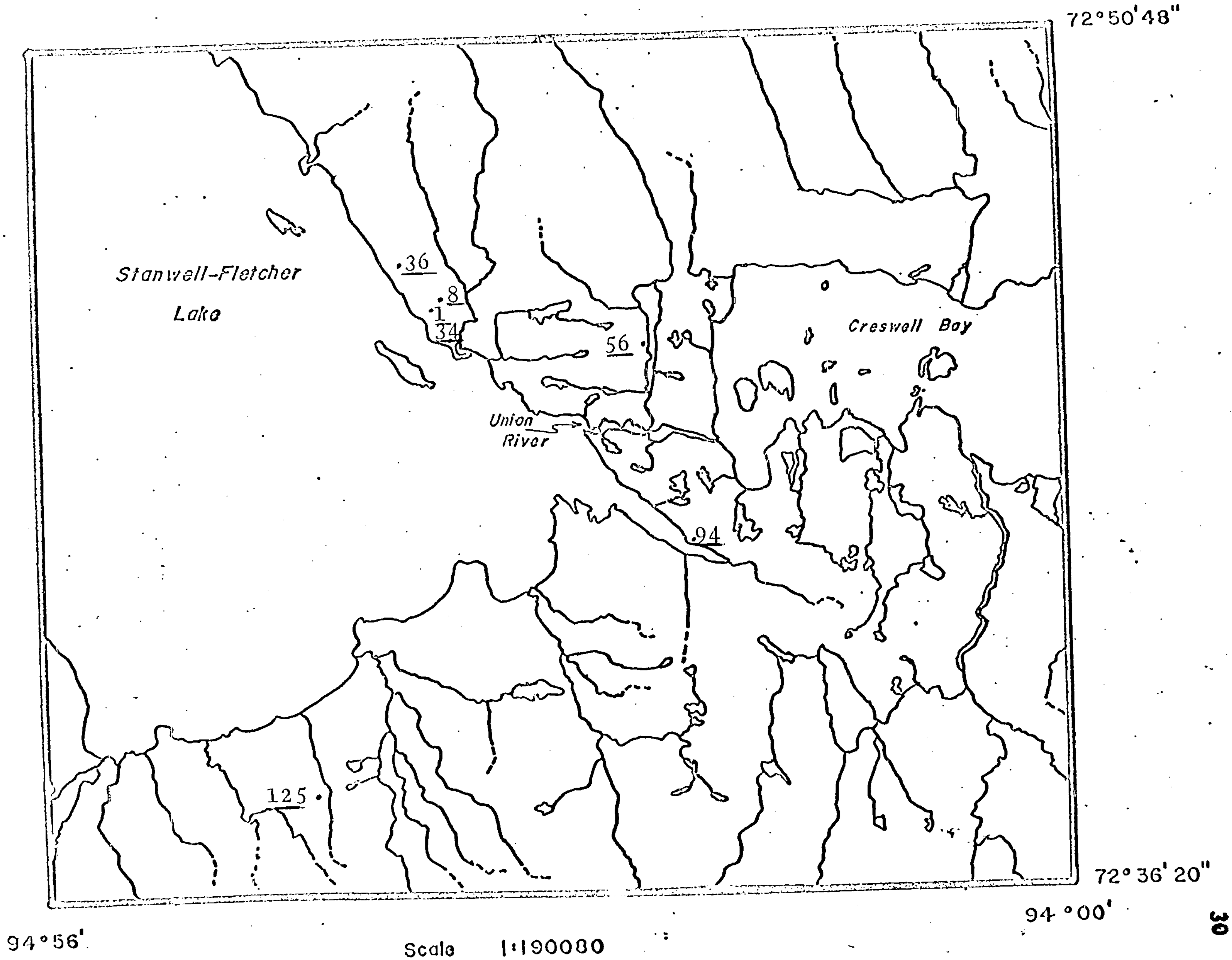

Figure 2: Location of Analysed Specimens

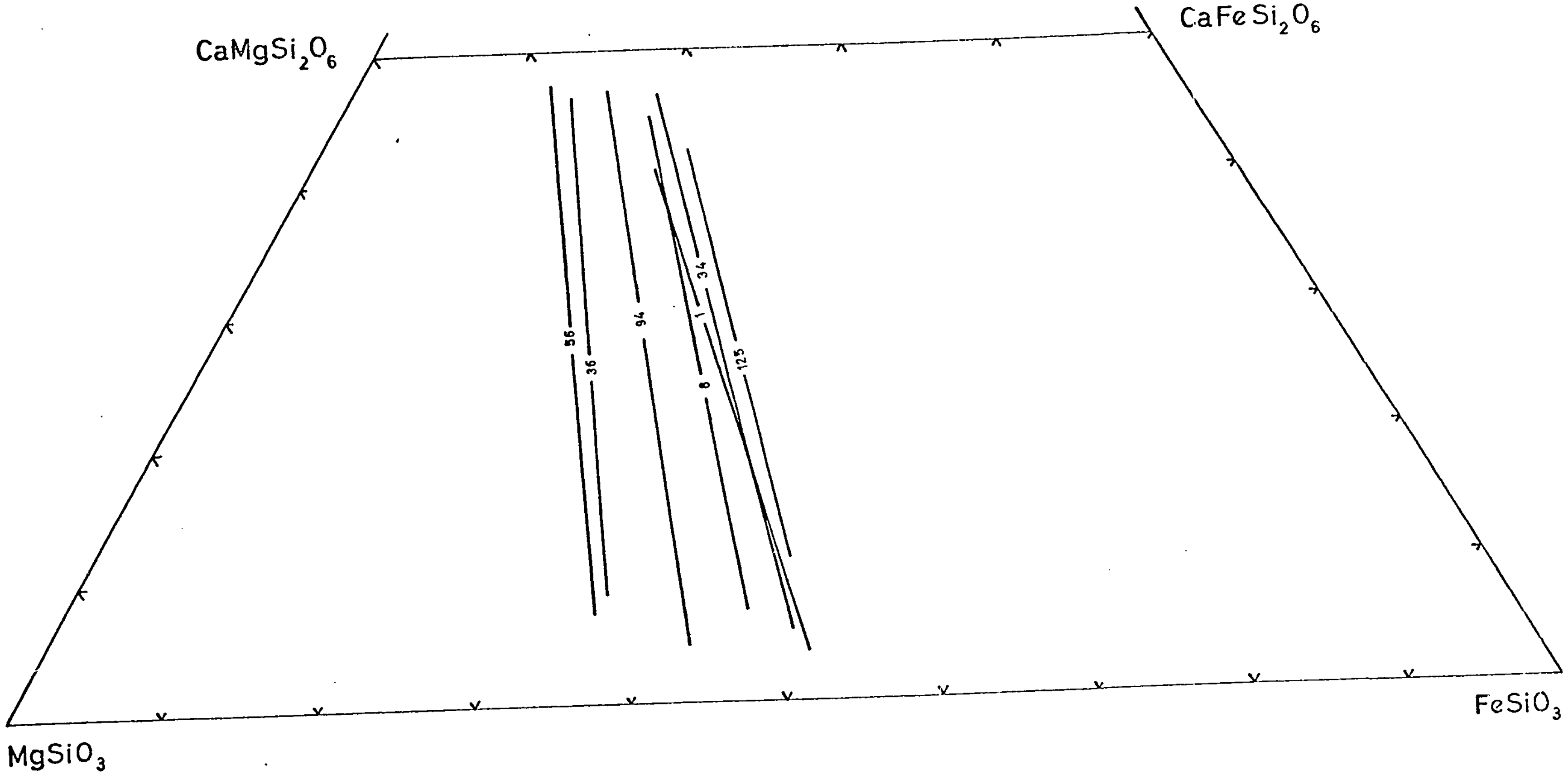

Figure 3: Tie lines joining coexisting orthopyroxene and calcic pyroxene from the seven studied specimens from Somerset Island. Plotted positions determined by chemical analyses.

DISTRIBUTION OF MAGNESIUM AND IRON

Within the system $CaSiO_3$ - $MgSiO_3$ - $FeSiO_3$ a two phase field can be defined containing orthopyroxene and monoclinic calcic pyroxene. With two phases and three components, Gibbs phase rule allows for a variance of one when pressure and temperature are defined.

That is $\omega = C+2-\varphi \equiv$ variance

becomes $\omega = C+0-\varphi \equiv 1$

Where ω is the variance of the system C is the number of components, 2 refers to the intensive variables, temperature and pressure and φ is the number of phases.

With a variance of one this allows for one intensive variable to change, and since temperature and pressure are fixed at equilibrium this intensive variable may be a mole fraction. In the case of orthopyroxene and clinopyroxene the variable mole fraction must be either magnesium or bivalent iron since calcium is what defines the difference between the two phases, orthopyroxene and the monoclinic calcic pyroxene. This point is further discussed in the chapter on calcium.

Since magnesium and iron occupy the same structural position in each phase the change in the mole fraction of one element in a phase will cause an inversely proportional change in the same phase.

Consider a rock composed of an equilibrium assemblage of phases, including orthopyroxene of the general formula (x, y) SiO_3 and calcic pyroxene of the general formula Ca(x, y) Si_2O_6 where x is the bivalent position occupied by Mg, Fe^{+2}, Mn, and y represents a minor element, trivalent or four valency, position occupied by Fe^{+3},Ti,Al.

Remembering that equilibrium is equivalent to reversible reaction, the following exchange equilibrium for major bivalent elements between co-existing pyroxenes (Kretz, 1963) may be considered:

$$\overset{\text{orthopyroxene (ss)}}{\overset{\upharpoonleft\downharpoonright}{MgSiO_3}} + \overset{\text{calcic pyroxene (ss)}}{\overset{\upharpoonleft\downharpoonright}{FeCaSi_2O_6}} \rightleftharpoons \underset{\text{orthopyroxene}}{\underset{\upharpoonleft\downharpoonright}{FeSiO_3}} + \underset{\text{calcic pyroxene}}{\underset{\upharpoonleft\downharpoonright}{MgCaSi_2O_6}} \qquad (a)$$

The requirement for equilibrium at a specified temperature and pressure is that the sum of the energy terms equals zero, which means that the summation of the energy of removing one mole of $MgSiO_3$ from orthopyroxene and one mole of $FeCaSi_2O_6$ from calcic pyroxene, plus the energy of reaction of the species to form one mole of $FeSiO_3$ and one mole of $MgCaSi_2O_6$, plus the energy of mixing one mole of $FeSiO_3$ in orthopyroxene and one mole of $MgCaSi_2O_6$ in calcic pyroxene, equals zero.

The energy term for removing one mole of $MgSiO_3$ from orthopyroxene is expressed by $RT\ln X_{MgSiO_3}$ for ideal solutions. For non-ideal solutions, this term becomes $RT\ln \lambda X_{MgSiO_3}$ where λ is the activity coefficient of $MgSiO_3$ in orthopyroxene. Another way of writing this energy term is $RT\ln X_{MgSiO_3} + \mu^E_{MgSiO_3}$ where $\mu^E_{MgSiO_3}$ is the excess chemical potential of $MgSiO_3$ in orthopyroxene. This incorporates the deviation of the solution from ideality, and because it simplifies the concept, it is used in this thesis.

In a simplified form, the five energy terms are as follows:

1) $RT\ln X_{MgSiO_3} + \mu^E_{MgSiO_3}$

2) $RT\ln X_{FeCaSi_2O_6} + \mu^E_{FeCaSi_2O_6}$

3) $G_{MgCaSi_2O_6} + G_{FeSiO_3} - G_{FeCaSi_2O_6} - G_{MgSiO_3} = \Delta G_a$

4) $-RT\ln X_{FeSiO_3} - \mu^E_{FeSiO_3}$

5) $-RT\ln X_{MgCaSi_2O_6} - \mu^E_{MgCaSi_2O_6}$

The sum of these terms, equated to zero yields:

$$K_{D(Mg-Fe)} = \frac{X_{MgSiO_3}}{1 - X_{MgSiO_3}} \cdot \frac{1 - X_{MgCaSi_2O_6}}{X_{MgCaSi_2O_6}} = \mathrm{Exp}\left[\frac{\Delta G_a + \mu_a^E}{RT}\right]$$

≡ Distribution coefficient with reference to Mg and Fe^{+2}.

The distributions of some elements between coexisting pyroxenes from Somerset Island will now be compared to the distributions of the same elements in similar rocks from other areas in the world.

A study of the Mg-Fe distribution between coexisting pyroxenes in metamorphic rocks shows that the mean $K_{D(Mg-Fe)}$ is equal to 0.5639, this value being arrived at by the method of arithmetical averages, and includes all analysed pyroxene pairs available from publications and from analysed specimens included in this thesis (Appendix C).

It was assumed at the time that the distribution of magnesium and iron between calcic pyroxene and orthopyroxene was ideal. The best fit curve determined by the least squares method shows an increase in the $K_{D(Mg-Fe)}$

values up to the mole fraction $X_{Mg}^{H} = 0.45000$ with the corresponding $X_{Mg}^{C} = 0.32668$ (1). Thereafter the K_D(Mg-Fe) values gradually decrease. This feature is represented graphically on figure 4, where the best fit curve is presented in comparison to the average K_D(Mg-Fe) = 0.5689 curve.

The simple, very open S shape illustrated by plotting $X^H/1-X^H)$ vs $X^C/(1-X^C)$ figures 5a, b, c) of the best fit curve suggests that only one of the components is non-ideal (mueller 1961). As it is generally accepted that the exchange of Fe for Mg in calcic pyroxene is ideal (Mueller 1961), the conclusion that one must arrive at is that the change in K_D(Mg-Fe) must be due to the non-ideality of the Mg to Fe exchange in orthopyroxene.

For practical purposes the deviation from ideality is so small as to be within the range of experimental error when a small number of specimens is involved. The arithmetical average is assumed to be sufficiently close to the true value.

The value arrived at for the average K_D(Mg-Fe) = 0.6019 (figure 6), for the Somerset Island rocks show that this value is greater than average value for charnokitic rocks identified from other locations with the exception of those described by Krank (1961) from

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(1) H = orthopyroxene; C = calcic pyroxene

Labrador, (Appendix E). The conclusion consistent with thermodynamic theory most probably is that these rocks reached equilibrium at a different temperature and pressure than most charnokitic rocks.

This point is elaborated on in the discussion of the variation of the distribution coefficients for coexisting pyroxenes with temperature and pressure.

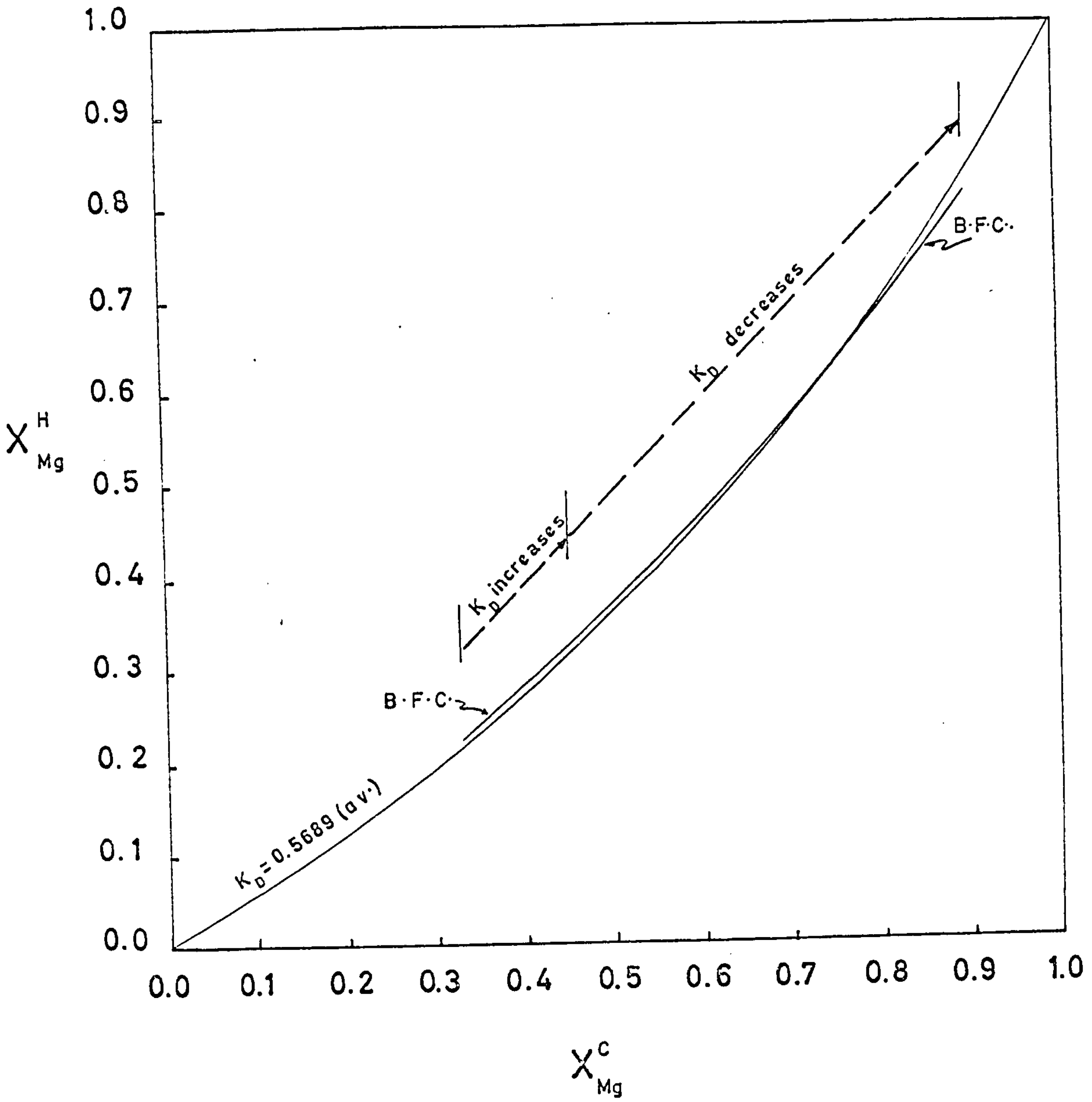


Figure 4: The average K_D value for Mg with reference to Fe is compared to the best fit curve (B.F.C.).

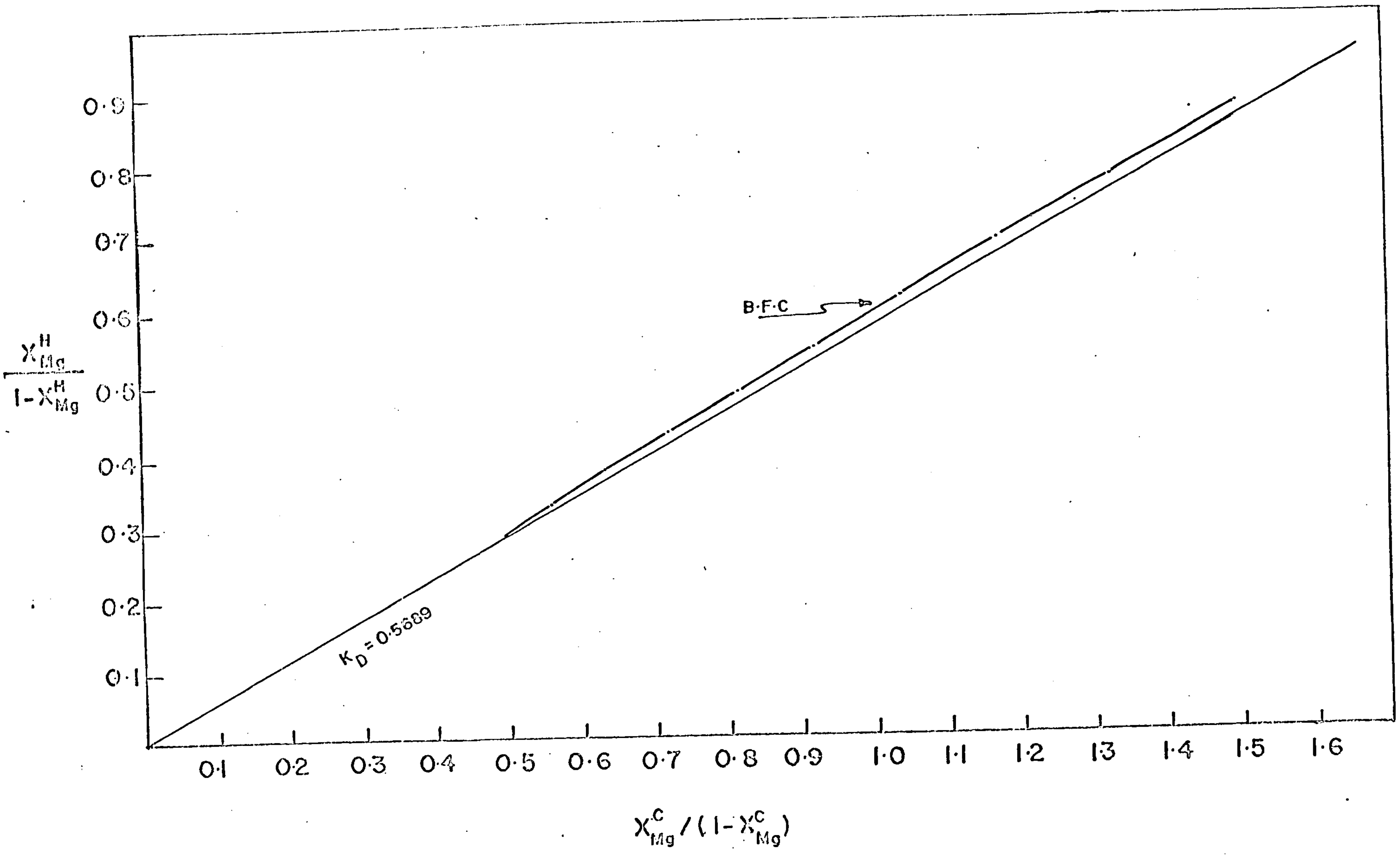


Figure 5A: Best fit curve (B.F.C.) of the coefficient of distribution with reference to Mg and Fe in comparison to the average coefficient of distribution curve.

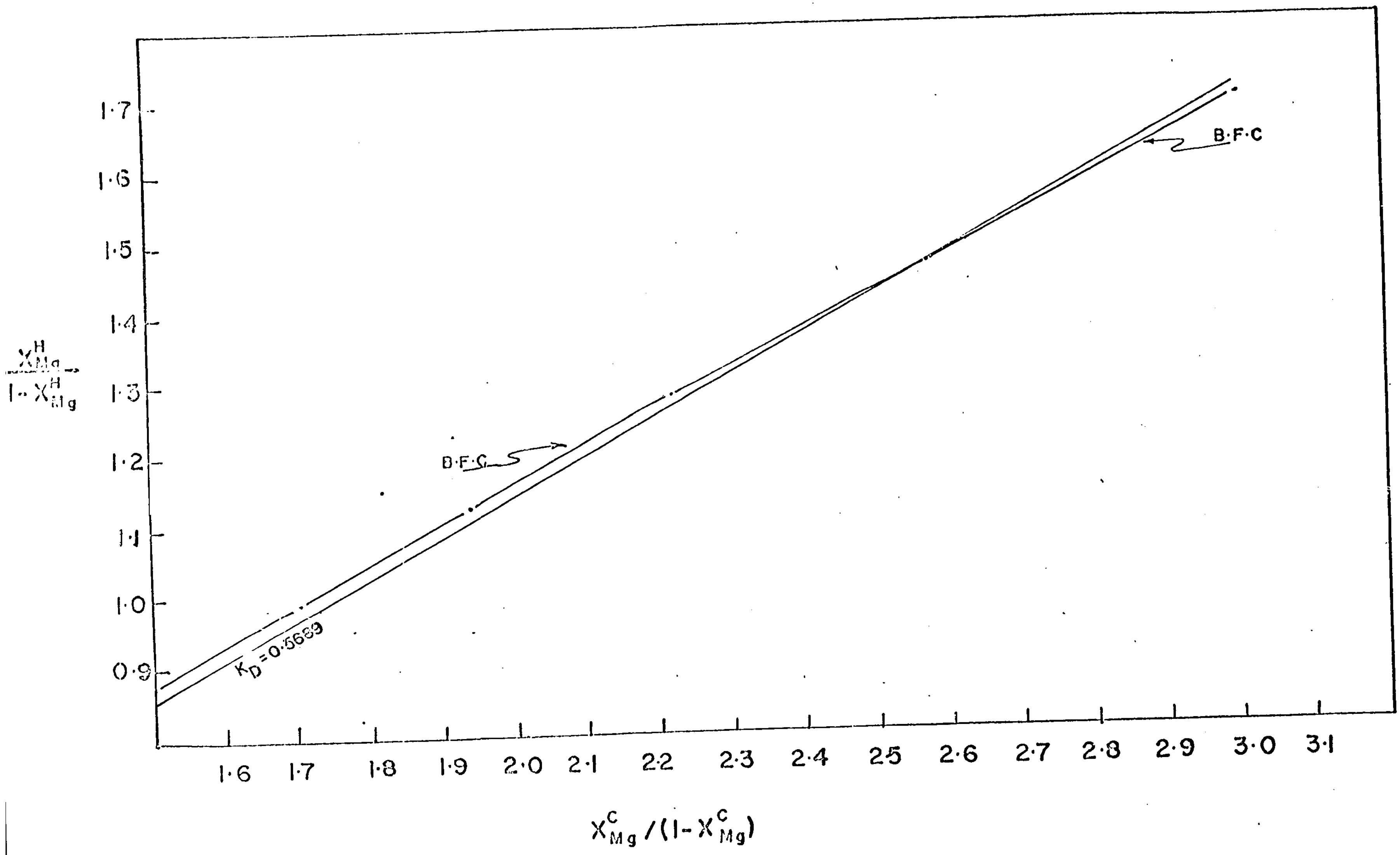


Figure 5B: Extension of part A.

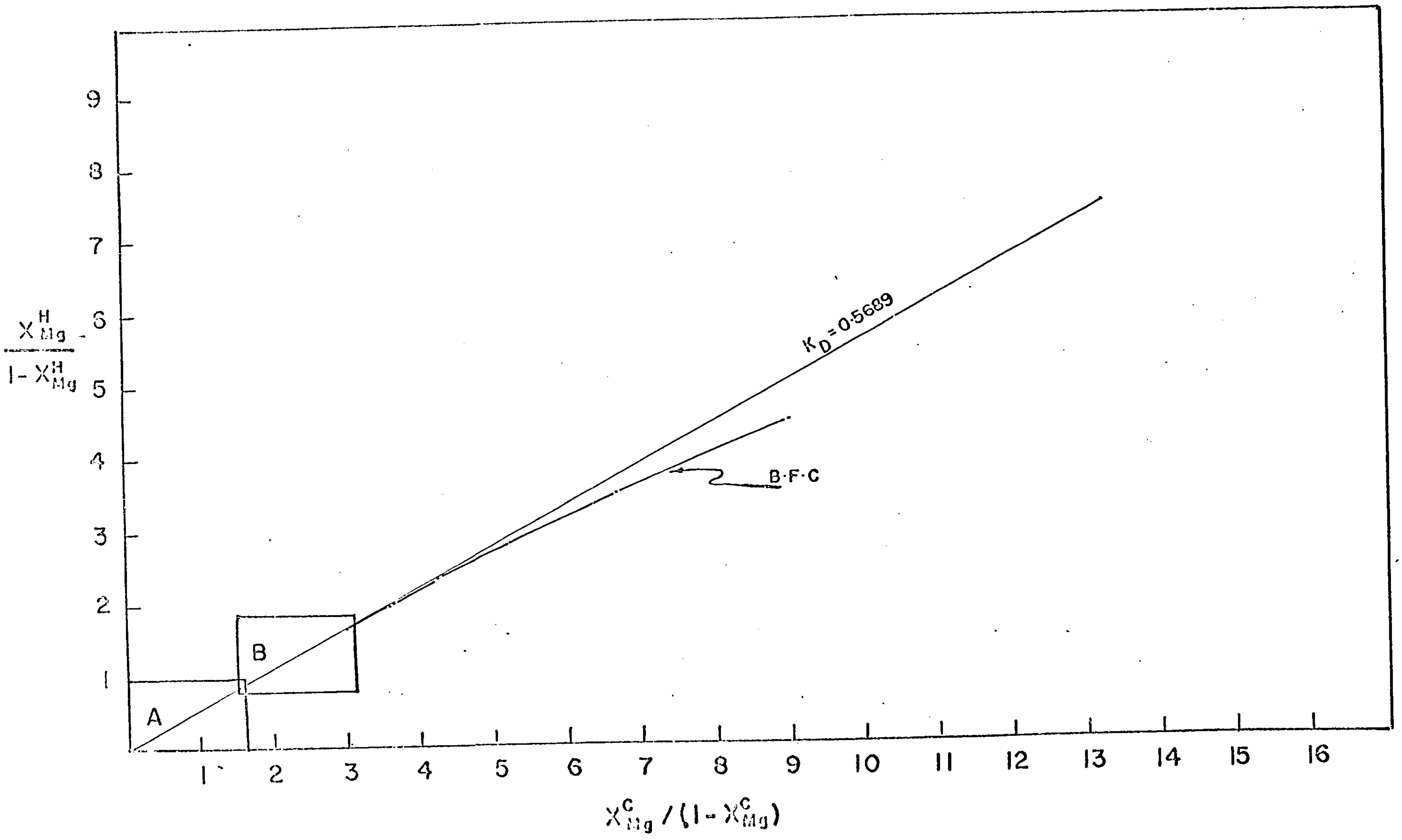


Figure 5C: Extension of part B at a scale 10x larger with outlined areas covered by figures 5A,B.

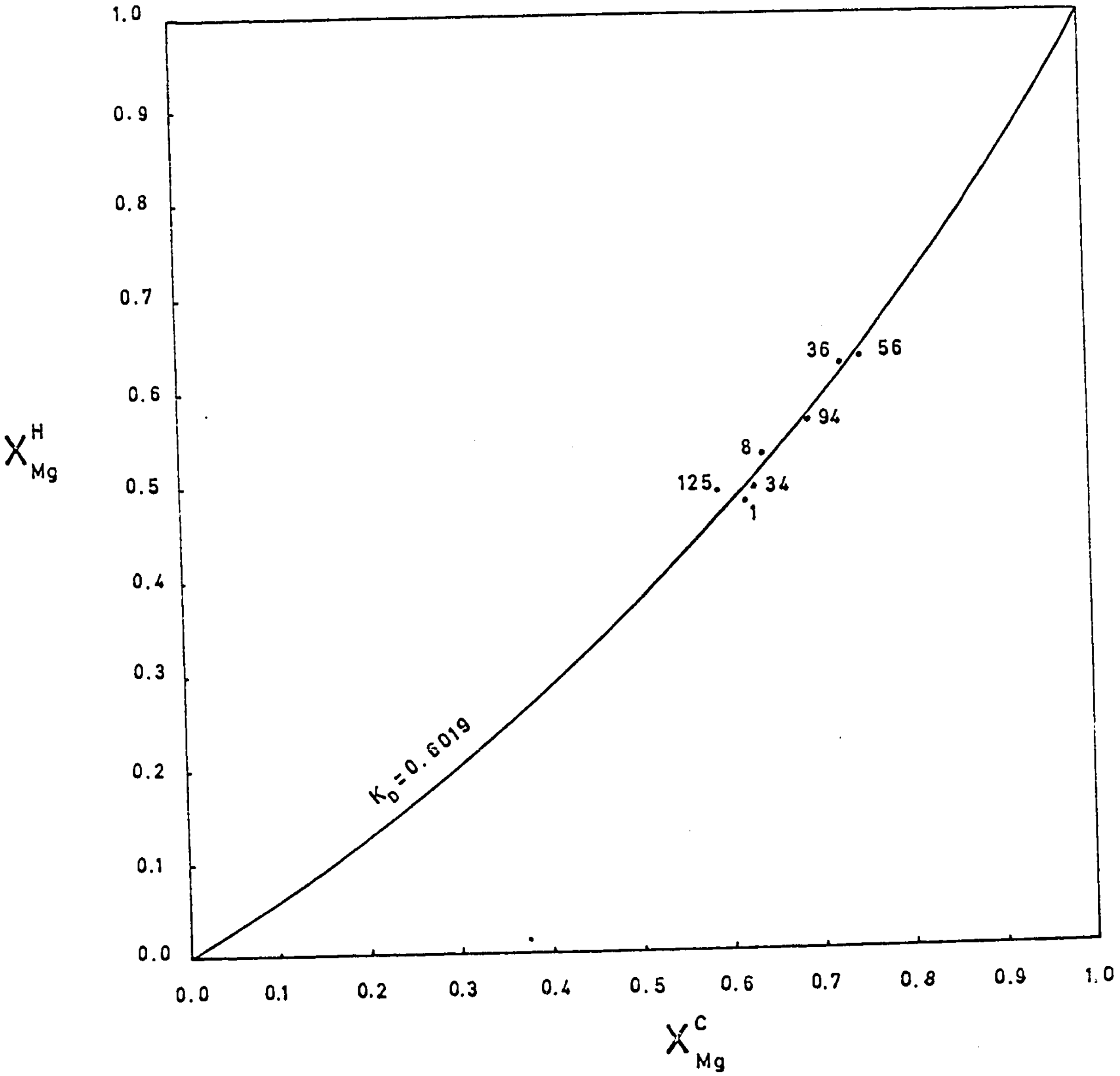


Figure 6: Average K_D(Mg-Fe) curve for the Somerset Island rocks.

DISTRIBUTION OF MANGANESE

As in the previous discussion, an exchange equilibrium for minor elements occupying the x position in pyroxenes can also be written. According to Kretz (1963), the exchange equilibrium of Mn between orthopyroxene of the simplified formula (Mg, Fe, Mn) SiO_3 and calcic pyroxene of simplified formula (Mg, Fe, Mn) $CaSi_2O_6$ is written as follows:

$$\begin{array}{ccc} \text{orthopyroxene (ss)} & & \text{calcic pyroxene (ss)} \\ \upharpoonleft\downharpoonright & & \upharpoonleft\downharpoonright \\ MnSiO_3 & + & (Mg,Fe)CaSi_2O_6 \rightleftharpoons \\ \text{orthopyrox ne (ss)} & & \text{calcic pyroxene (ss)} \\ \upharpoonleft\downharpoonright & & \upharpoonleft\downharpoonright \\ (Mg,Fe)SiO_3 & + & MnCaSi_2O_6 \end{array}$$

The energy terms of this exchange equilibrium must equal zero at a specified temperature and pressure. These energy terms are:

$$RT\ln X_{MnSiO_3} + \mu^E_{MnSiO_3}$$

$$RT\ln X_{(Mg,Fe)CaSi_2O_6} + \mu^E_{(Mg,Fe)SiO_3}$$

$$G_{MnSiO_3} + G_{(Mg,Fe)CaSi_2O_6} - G_{(Mg,Fe)SiO_3} - G_{MnCaSi_2O_6} = \Delta G_b$$

$$-RT\ln X_{(Mg,Fe)SiO_3} - \mu^E_{(Mg,Fe)SiO_3}$$

$$-RT\ln X_{MnCaSi_2O_6} - \mu^E_{MnCaSi_2O_6}$$

The sum of these terms equated to zero yields

$$K_{D(Mn-Mg,Fe)} \equiv \frac{X_{MnSiO_3}}{1-X_{MnSiO_3}} \cdot \frac{1 - X_{MnCaSi_2O_6}}{X_{MnCaSi_2O_6}}$$

$$= \exp.\left[\frac{\Delta G_b + \mu_b^E}{RT}\right]$$

Since ΔG_b contains the terms $G_{(Mg,Fe)CaSi_2O_6}$ and $G_{(Mg,Fe)SiO_3}$ and μ_b^E contains the terms $\mu^E_{(Mg,Fe)SiO_3}$ and $\mu^E_{(Mg,Fe)CaSi_2O_6}$, the terms ($\Delta G_b + \mu_b^E$) is dependent on the Mg:Fe ratio in both phases. Consequently $K_{D(Mn-Mg,Fe)}$ must be dependent on the Mg:Fe ratio in both phases, but since these ratios are interrelated by the equation:

$$K_{D(Mg-Fe)} \equiv \frac{X_{MgSiO_3}}{1-X_{MgSiO_3}} \cdot \frac{1 - X_{MgCaSi_2O_6}}{X_{MgCaSi_2O_6}}$$

$$= \exp.\left[\frac{\Delta G_a + \mu_a^E}{RT}\right]$$

The Mg:Fe ratio in only one mineral forms an <u>independent</u> variable.

The values obtained for the distribution coefficient in the different specimens from Somerset Island show very little deviation from the mean distribution coefficient $K_{D(Mn-Fe,Mg)} = 1.1656$ of these same rocks (fig. 7). Therefore, it can be said that equilibrium was established between orthopyroxene and calcic pyroxene in relation to manganese.

The distribution of manganese in all charnockitic rocks is more erratic than those under study in this thesis (fig. 8), but a definite trend is noticeable, and a mean value for distribution coefficient was obtained at $K_D = 1.2283$.

Since the deviation from the mean distribution coefficient is not very large, even when a large number of specimens from various sources are considered, it can be said that Mn does occupy the bivalent position and substitutes for Mg and/or bivalent Fe.

The influence of variations in the mole fraction of Mn in either orthopyroxene or calcic pyroxene on the value of $K_{D(Mg-Fe)}$ as outlined by Kretz (1963), is not apparent when considering all studied pyroxene pairs or when considering the pyroxene pairs from Somerset Island.

The reason for not detecting this dependence may be due to the influence of the manganese mole fraction being very small, or to analytical error; the likelihood of both reasons are very high, the latter because of the small quantities of Mn involved.

When the mean distribution coefficient for Mn in metamorphic rocks, $K_{D(Mn-Mg,Fe)} = 1.2283$, is compared to the mean value obtained from known igneous rocks $K_{D(Mn-Mg-Fe)} = 1.013$ as studied by Kretz (1963), the assumption that the trend of the value of the $K_{D(Mn-Mg,Fe)}$ tends towards unity with increasing temperature can be made.

Since the distribution coefficient of manganese in metamorphic and igneous rocks is greater than unity, we can note that the values of $K_{D(Mn)}$ decrease with increasing temperature, that is that this displacement is in the opposite direction to the displacement of the distribution coefficient of magnesium over the same temperature interval.

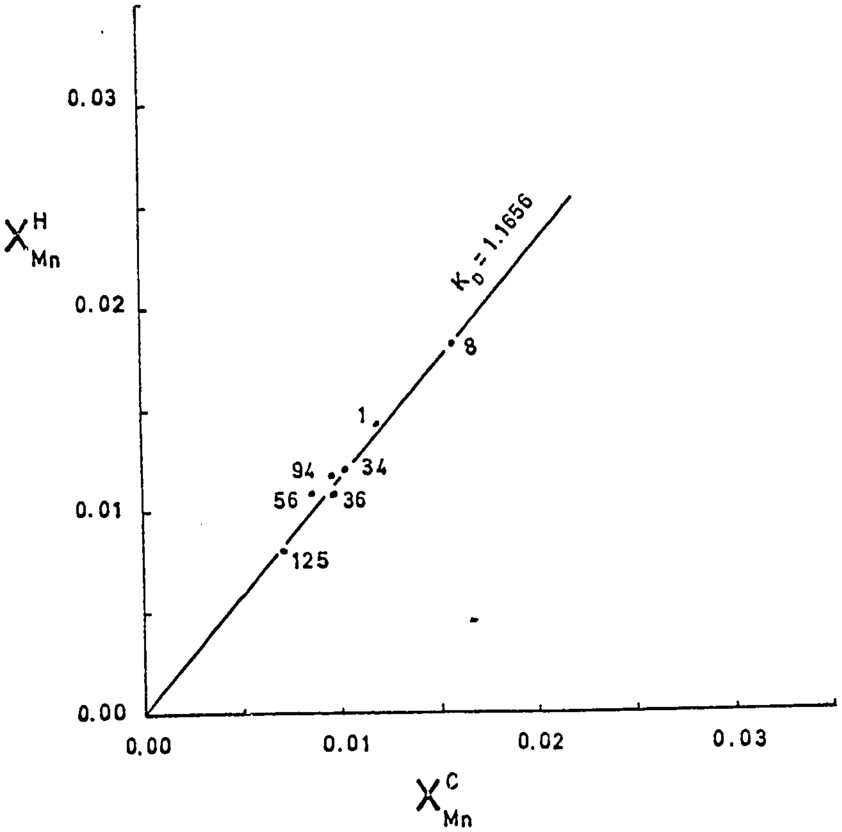


Figure 7: Average K_D(Mn-Mg,Fe) for the Somerset Island rocks.

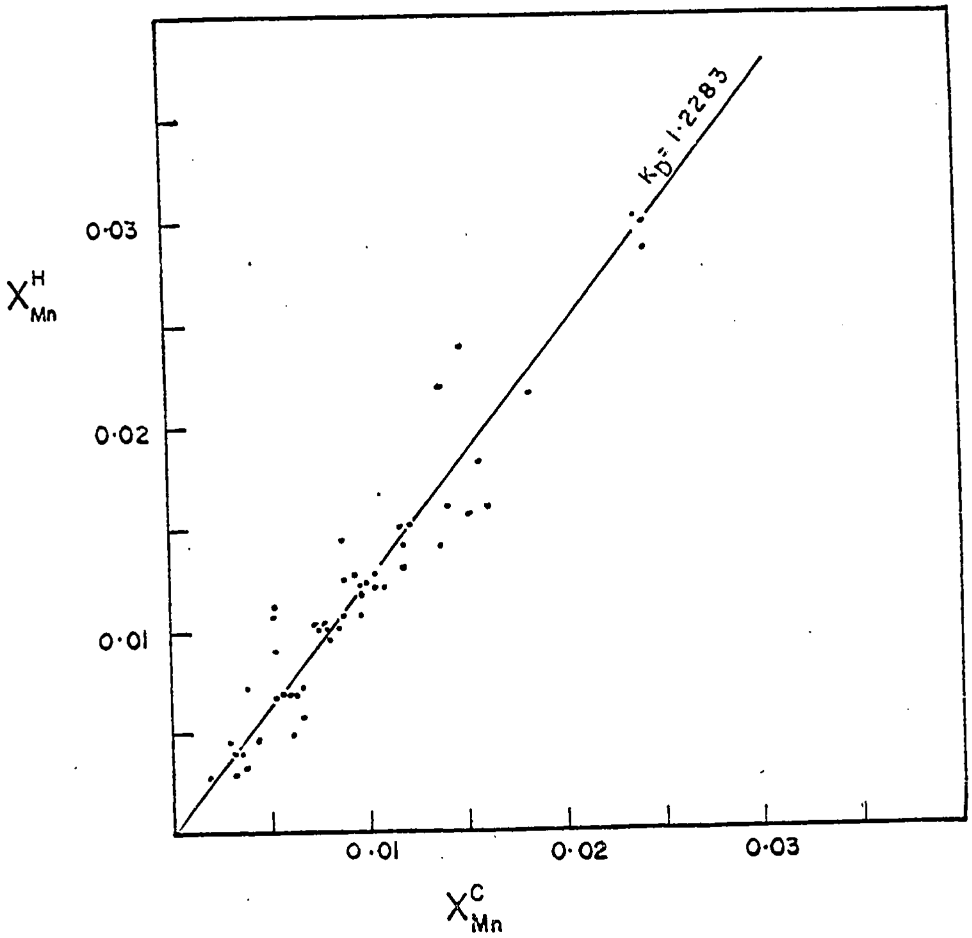


Figure 8: Position of all analysed mole fraction values for Mn from pyroxene pairs in metamorphic rocks. The line represents an average K_D(Mn-Mg,Fe) for all plotted pyroxene pairs.

DISTRIBUTION OF CALCIUM

The distribution of calcium between orthopyroxene and calcic pyroxene cannot be considered in an exchange equilibrium since calcium does not substitute for a bivalent ion of the x position in calcic pyroxene, but occupies a position of its own forming the simplified formula (x,y) $CaSi_2O_6$ of calcic pyroxene.

The presence of calcium in orthopyroxene can be explained as the solution of unit cells of calcic pyroxene in the structure of orthopyroxene.

Similarly the deviation of calcic pyroxene from ideality can be explained by the solution of unit cells of orthopyroxene in calcic pyroxene. The relationship is similar to the subsolidus exsolution curve of the albite-potassium feldspar system.

With this sort of relationship, the solution of calcic pyroxene in orthopyroxene and orthopyroxene in calcic pyroxene is determined by a solubility function which is dependent on temperature and pressure.

The best representation of calcium distribution is on the subsolidus exsolution surface for coexisting pyroxenes in the system $CaSiO_3$ - $MgSiO_3$ - $FeSiO_3$. The study of this type of element distribution is beyond the scope of this thesis.

DISTRIBUTION OF TRIVALENT IRON AND TITANIUM

The distribution of trivalent iron (Fe^{+3}) and titanium (Ti) in relationship to the bivalent elements, is apparently erratic, though no physical evidence for equilibrium is evident in rocks of Somerset Island and none is reported for the rocks from the other locations referred to in this study.

The variation in values for $K_D(Fe^{+3} - Mg,Fe)$ and for $K_D(Ti-Mg,Fe)$ (Appendix C) can be explained by:

1) Contamination of the samples by iron or iron-titanium oxides.

2) High error in analytical methods because of the small quantities of trivalent iron and titanium or,

3) No exchange equilibrium being established between elements in the bivalent position and those in the trivalent position.

It must be noted here that the oxidation state of Ti in pyroxenes is not known. The possibility of contamination is high, since all the rock specimens studied in this thesis contain magnetite and possibly ilmenite. As to analytical error, the degree of variability in the values obtained for $K_D(Fe^{+3} - Mg,Fe)$ and for $K_D(Ti-Mg,Fe)$ far exceeds that possible due to analytical error.

The third possibility must be considered. Because of the different oxidation state, it is not possible to write an exchange equilibrium where Fe^{+3} is exchanged with a bivalent element without inducing an unstable situation with regard to electrons. If Ti is assumed to be trivalent, in the considered coexisting pyroxenes, an exchange equilibrium can be written between Fe^{+3} and Ti^{+3}. Evidence for this is the apparent equilibrium in regard to the distribution coefficient, $K_D(Ti^{+3} - Fe^{+3})$ of specimens from specific locations, especially those from Bengal (Sen and Rege, 1966).

Assuming that titanium is trivalent in pyroxenes, an exchange equilibrium involving only the z position can be written:

$$\begin{array}{lcll}
\text{orthopyroxene (ss)} & & \text{calcicpyroxene (ss)} & \\
\upharpoonleft\downharpoonright & & \upharpoonleft\downharpoonright & \\
Fe^{+3}x(Al,Si)O_3 & + & Ti^{+3}xCa(Al,Si)_2O_6 & \rightleftharpoons \\
\rightleftharpoons Ti^{+3}x(Al,Si)O_3 & + & Fe^{+3}xCa(Al,Si)_2O_6 & \\
\upharpoonleft\downharpoonright & & \upharpoonleft\downharpoonright & \\
\text{orthopyroxene (ss)} & & \text{calcicpyroxene (ss)} &
\end{array}$$

where x is the bivalent position.

Following the procedure outlined previously, the sum of the energy terms involved in the equation must equal zero at equilibrium.

These terms are:

$$RT\ln X_{Fe^{+3}x(Al,Si)O_3} + \mu^E_{Fe^{+3}x(Al,Si)O_3}$$

$$RT\ln X_{Ti^{+3}xCa(Al,Si)_2O_6} + \mu^E_{Ti^{+3}xCa(Al,Si)_2O_6}$$

$$G_{Fe^{+3}x(Al,Si)O_3} + G_{Ti^{+3}xCa(Al,Si)_2O_6} - G_{Ti^{+3}x(Al,Si)O_3} - G_{Fe^{+3}xCa(Al,Si)_2O_6} = \Delta G_c$$

$$-RT\ln X_{Ti^{+3}x(Al,Si)O_3} - \mu^E_{Ti^{+3}x(Al,Si)O_3}$$

$$-RT\ln X_{Fe^{+3}xCa(Al,Si)_2O_6} - \mu^E_{Fe^{+3}xCa(Al,Si)_2O_6}$$

These terms equated to zero give:

$$K_D(Ti\text{-}Fe^{+3}) = \frac{X^H_{Ti}}{1 - X^H_{Ti}} \cdot \frac{1 - X^C_{Ti}}{X^C_{Ti}} = \exp. \left[\frac{\Delta G_c + \mu^E_c}{RT}\right]$$

where X_{Ti} is the mole fraction of Ti^{+3} in the z position and is equal to $Ti^{+3}/Ti^{+3}+Fe^{+3}$.

Possible deviation of $K_D(Ti^{+3}\text{-}Fe^{+3})$ at equilibrium may be due to the presence of a third component in the z position such as Al.

Difficulties will occur in detecting equilibrium in this exchange due to high possibility of contamination by magnetite, hematite or ilmenite.

In the natural distribution of Ti^{+3} and Fe^{+3}, we can see on Figure 9 that certain groups have an apparent trend, especially the four specimens mentioned previously. If we consider the specimens from Somerset Island, excluding #1 and #125, for which only total iron was determined and specimen #36 because of its extreme deviation from values obtained for the other rocks in the area, we get a reasonable distribution that might indicate equilibrium conditions relative to trivalent iron and titanium (figure 9).

Among factors other than temperature and total pressure possibly influencing the distribution coefficient of Ti^{+3} to Fe^{+3}, are the presence of other trivalent elements such as Al^{+3}, Cr^{+3}, and the influence of oxygen pressure or other volatiles. Further work is warranted along these lines but is beyond the scope of this study.

DISTRIBUTION COEFFICIENT WITH REFERENCE TO TRIVALENT IRON (Fe^{+3}) AND TRIVALENT TITANIUM (Ti^{+3})

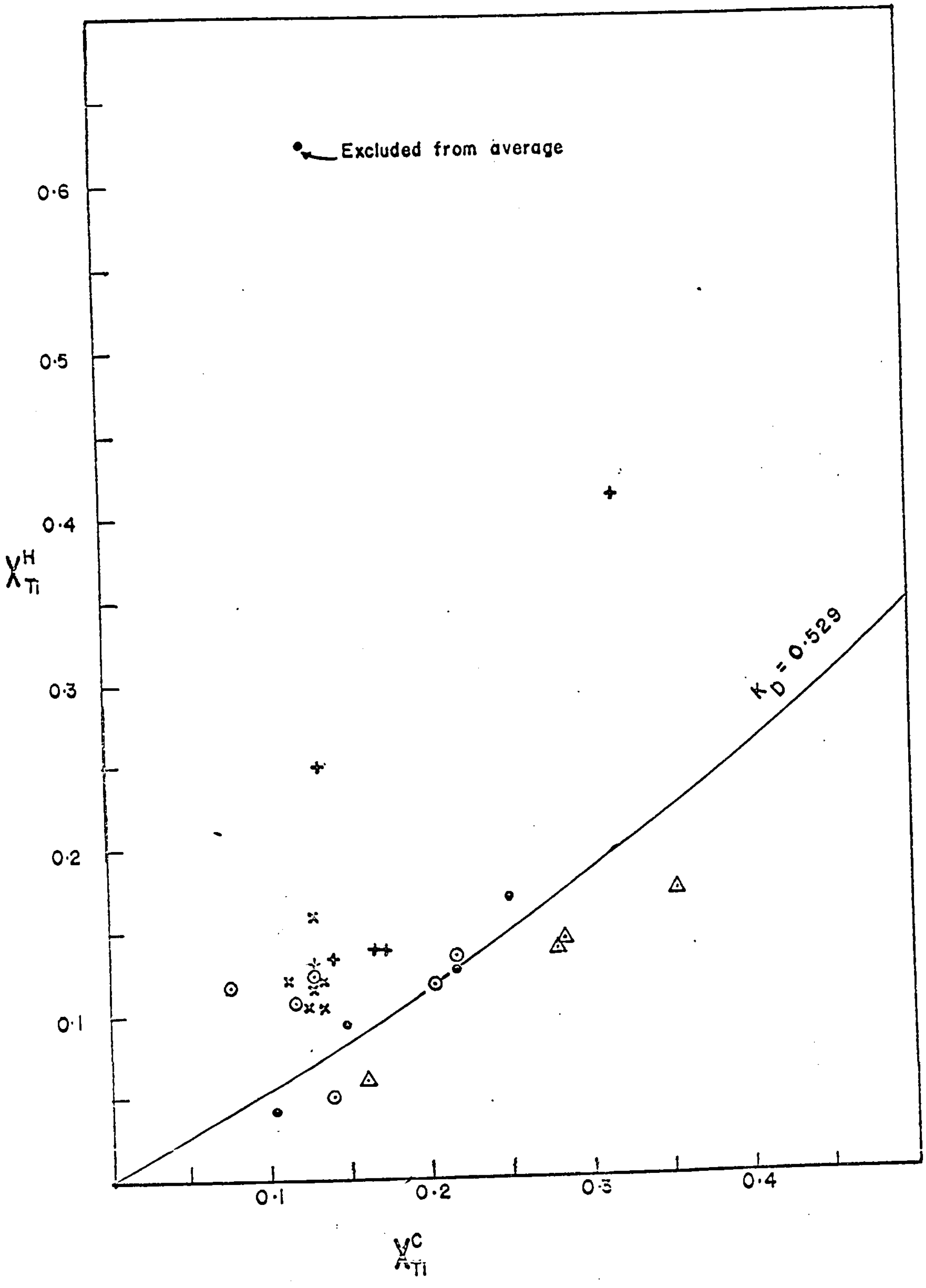
TABLE 2

Sample No.	$X^{H}_{Ti-Fe^{+3}}$	$X^{C}_{Ti-Fe^{+3}}$	$K_D(Ti-Fe^{+3})$	Source
2 (8)	0.1659	0.2508	0.5934	
3 (34)	0.0951	0.1471	0.6091	Somerset Island, N.W.T.
4 (36)	0.6230	0.1295	11.1091*	
5 (56)	0.0435	0.1022	0.3992	J.F. Giguere, 1966
6 (94)	0.1277	0.2157	0.5317	
		Average =	0.533	

*Excluded from Average

Sample No.	$X^{H}_{Ti-Fe^{+3}}$	$X^{C}_{Ti-Fe^{+3}}$	$K_D(Ti-Fe^{+3})$	Source
23	0.1075	0.1368	0.198	
24	0.1270	0.1362	0.750	
25	0.1253	0.1102	0.348	Madras, India
26	0.1157	0.1271	0.576	Howie, 1955
27	0.1087	0.1225	0.327	
28	0.1637	0.1265	0.241	
		Average =	0.406	
29	0.1300	0.1266	0.113	
30	0.413	0.3185	0.122	Broken Hill, N.S. Wales
31	2.500	0.1312	0.498	Australia
32	0.1422	0.1708	0.612	Binns, 1962
33	0.1432	0.1592	0.713	
34	0.1377	0.1401	0.837	
		Average =	0.482	

Sample No.	$X^{H}_{Ti-Fe^{+3}}$	$X^{C}_{Ti-Fe^{+3}}$	$K_D(Ti-Fe^{+3})$	Source
42	0.1250	0.1302	0.7419	
43	0.1064	0.1168	0.8998	Pennsylvania and Delaware, U.S.A.
44	0.1153	0.0764	1.5746	
45	0.0935	0.1322	0.9532	
46	0.1194	0.2045	0.5271	
47	0.0504	0.1408	0.3231	Clavan et al, 1954 Norton & Clavan, 1959
48	0.1355	0.2105	0.5876	
		Average =	0.775	
52	0.0643	0.1612	0.3573	
53	0.1453	0.2892	0.4177	Bengal, India
54	0.1417	0.2802	0.4239	
55	0.1752	0.3512	0.3923	Sen and Rege, 1966
		Average =	0.399	



- ∘ Somerset Island, N.W.T.; Giguere, 1967.
- △ Bengal, India; Sen and Rege, 1966.
- × Madras, India; Howie, 1955.
- ⊙ Penn and Del-U.S.A.; Norton and Clavan, 1959, Clavan et al, 1954.
- ✛ Broken Hill, N. S. Wales, Aus.; Binns, 1962.

Figure 9: Position of listed analyses for Ti and average line for $K_D(\text{Ti-Fe}^{+3})$

EFFECT OF TEMPERATURE AND PRESSURE

In the expression:

$$K_{D(Mg-Fe)} = \frac{X^H_{Mg}}{1-X^H_{Mg}} \cdot \frac{1 - X^C_{M}}{X^C_{Mg}}$$

$$= \exp\left[\frac{\Delta G_a + \mu^E_a}{RT}\right]$$

μ^E_a, which is a sum of the four excess partial free energy terms (page 35) must initially be expected to depend on the mole fractions of Mg and Fe. We find that $K_{D(Mg-Fe)}$ varies only a very small amount as a function of X^C_{Mg}, or X^H_{Mg} (Fig. 4). Therefore, the variation in μ^E_a is so small that the following simplified expressions for temperature and pressure dependence can be used. These expressions were developed by Kretz (1963).

Temperature:

$$\frac{\partial \ln K_{D(Mg-Fe)}}{\partial(1/T)} = \frac{1}{R}\left[\frac{\partial(\Delta G_a/T)}{\partial(1/T)} + \frac{\partial(\mu^E_a/T)}{\partial(1/T)}\right]$$

$$= \frac{\Delta H_a + h^E_a}{R}$$

where h^E_a is defined as $\partial\mu^E_a/\partial(1/T)$

Similarly the pressure dependence may also be written:

$$\frac{\partial \ln K_{D(Mg-Fe)}}{\partial P} = \frac{1}{RT}\left[\frac{\partial \Delta G_a}{\partial P} + \frac{\partial \mu_a^E}{\partial P}\right]$$

$$= \frac{\Delta V_a + v_a^E}{RT}$$

where v_a^E is defined as $\partial \mu_a^E / \partial P$.

In the preceding discussions the very small variation of μ_a^E (or its equivalent expressed by activity coefficients) was taken to indicate that for all practical purposes, within the range of T,P, and mole fraction under consideration both pyroxene phases can be treated as being close to ideal mixture. If they are treated as such, the four terms comprising μ_a^E vanish, and the expressions for temperature and pressure dependence are simplified by the disappearance of h_a^E and v_a^E.

Kretz (1963) outlined the relationship of $\ln K_{D(Mg-Fe)}$ vs. 1/T (Figure 10) from the information presented in Table (3). Using this diagram and a similar function on $\ln K_{D(Mg-Fe)}$ vs. P a three dimensional diagram can be constructed with the axes 1/T, P, and $\ln K_{D(Mg-Fe)}$ as a function of 1/T and P.

Lines of equal $\ln K_{D(Mg-Fe)}$ can then be projected on a base formed of the axes of P and 1/T (Figure 12 $\ln K_{D(Mg)}$ lines). The resultant diagram shows lines of equal $\ln K_{D(Mg-Fe)}$ on a two dimensional pressure-temperature diagram. Since $\ln K_{D(Mg-Fe)}$ is a near linear function of P and of 1/T the spacing of the equal $\ln K_{D(Mg-Fe)}$ will be regular and almost straight. With this diagram for any given $K_{D(Mg-Fe)}$ we can have a variety of P. and T. possibilities along a line of equal $K_{D(Mg-Fe)}$.

If a similar diagram utilising the axes $\ln K_{D(Mn-Mg,Fe)}$ P and 1/T is constructed using the data for manganese in the same rocks as used for deriving the magnesium function (table 3), a plane describing the $\ln K_{D(Mn-Mg,Fe)}$ as a function of P and 1/T is derived.

Since the concentration of Mn is small in naturally occurring pyroxene pairs and the influence of Mg:Fe ratio on the distribution coefficient of manganese is not detectable, the function of $\ln K_{D(Mn)}$ vs. 1/T and $\ln K_{D(Mn)}$ vs. P will be near linear functions. Therefore, $\ln K_{D(Mn)}$ as a function of P and 1/T will be a nearly flat plane in the cartesian system, $\ln K_{D(Mn)}$, P, 1/T.

Since the coefficient of distribution of Mn approaches unity from a direction opposite to that of

Mg, the lines of equal $\ln K_{D(Mn)}$ projected onto the same P vs. 1/T base will be of opposite slope to those of $\ln K_{D(Mg-Fe)}$ (figure 12, lines labelled $\ln K_{D(Mn)}$). It is assumed that $K_{D(Mg-Fe)}$ and $K_{D(Mn-Mg,Fe)}$ reached equilibrium at the same temperature and pressure within the same rock or group of rocks from a particular region. If this assumption is correct, the projection onto the common P vs. 1/T base of the tie line joining the value for $\ln K_{D(Mg)}$ and $\ln K_{D(Mn)}$ in the same rock or group of rocks will be a point which will be the equilibrium T and P for both $K_{D(Mg-Fe)}$ and $K_{D(Mn-Mg,Fe)}$, that is the tie line must be parallel to the common $\ln K_{D(Mn-Mg,Fe)}$ axis.

With this new diagram, if the values for $K_{D(Mg-Fe)}$ and $K_{D(Mn-Mg,Fe)}$ are known a value for temperature (°C) and pressure in atmospheres (Atm.) or depth in kilometres (Km.) (Turner and Verhoogen, 1960), can be derived.

The values on this diagram are tentative and the actual position and shape of the projected $\ln K_D$ planes can be experimentally determined.

On figure 12 are plotted various rocks or groups of rocks (A_1, A_2, A_3) including those used by Kretz and the author for positioning of the equal

K_D lines. It may be noted that other points which represented published analysis of coexisting pyroxenes and those studied in this thesis all fall well within the temperature and pressure range expected for granulites.

It must be pointed out that all rocks studied are assumed to be at equilibrium so for this reason contact metamorphic rocks were avoided because they possibly have not reached equilibrium.

ESTIMATES OF EQUILIBRATION TEMPERATURES AND PRESSURES FOR SELECTED ROCKS
(Modified from Kretz, 1963)

TABLE 3

Reference No.	K_D(Mg-Fe)	K_D(Mn-Mg,Fe)	Rock	T/° C.	P/Atm.
A1	0.51) .53) .55) 0.552 .56) .56) 0.60)	1.0) 1.8) 1.7) 0.84) 1.29 1.4) 1.0)	Charnockite series, granulite facies; Madras, India; Howie, 1955.	670*	5,000+
A2	0.686	1.16	Porphyritic gabbro, Uwekahuna "laccolith"; Kilauea; Muir and Tilley, 1957.	1,000+ +	15**
A3	0.71) .72) 0.729 .74) 0.75)	0.50) 1.3) 0.81 0.59 0.84)	Skaergaard Complex; Greenland; Brown, 1957.	1,150//	1,250 ± 250#

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* Some estimates of temperature for the granulite facies are as follows: above 600° C. (Fyfe and Turner, 1958, p. 161 and p. 154); 550° - 650° C. (Ramberg, 1952, p. 161); 650° - 750° C. for Indian Charnockite series (R. A. Howie, personal communication, to Kretz, 1963).

+ Estimate by R. Kretz based partly on conclusions of Barth (1952, p. 350).

‡ Equilibration temperature is taken as solidification temperature. Experimentally measured temperatures, using Hawaiian basalts range from 1040° to 1090° C. (Yoder and Tilley, 1957). Some lavas have not solidified at 900° - 1050° C. (G. A. Macdonald, personal communication to Kretz, 1963).

** Value obtained by calculation based on the following information provided by G. A. Macdonald (personal communication to Kretz, 1963). "Laccolith" crystallized beneath a cover of approximately 200 feet of basaltic rock of density 2.5.

// Brown (1957) with modification (personal communication to Kretz, 1963).

Estimate of G. M. Brown (personal communication to Kretz, 1963).

In Diagrams 10, 11, 12, the Following Notations are Used

A_1; Howie, 1955, Madras, India.

A_2; Muir and Tilley, 1957; Kilauea, Hawaii.

A_3; Brown, 1957; Skaergaard Complex, Greenland.

NC; Norton and Clavan, 1959, Penn. and Del., U.S.A.

Banno: Banno et al 1964, Lutzow-Holm Bay, Antartica.

SR: Sen and Rege, 1966, Bengal, India.

Binns: Binns 1962, Broken Hill, N.S. Wales, Australia.

K.: Krank, 1951; Quebec.

J.G.: Giguere, 1967; Somerset Island, N.W.T.

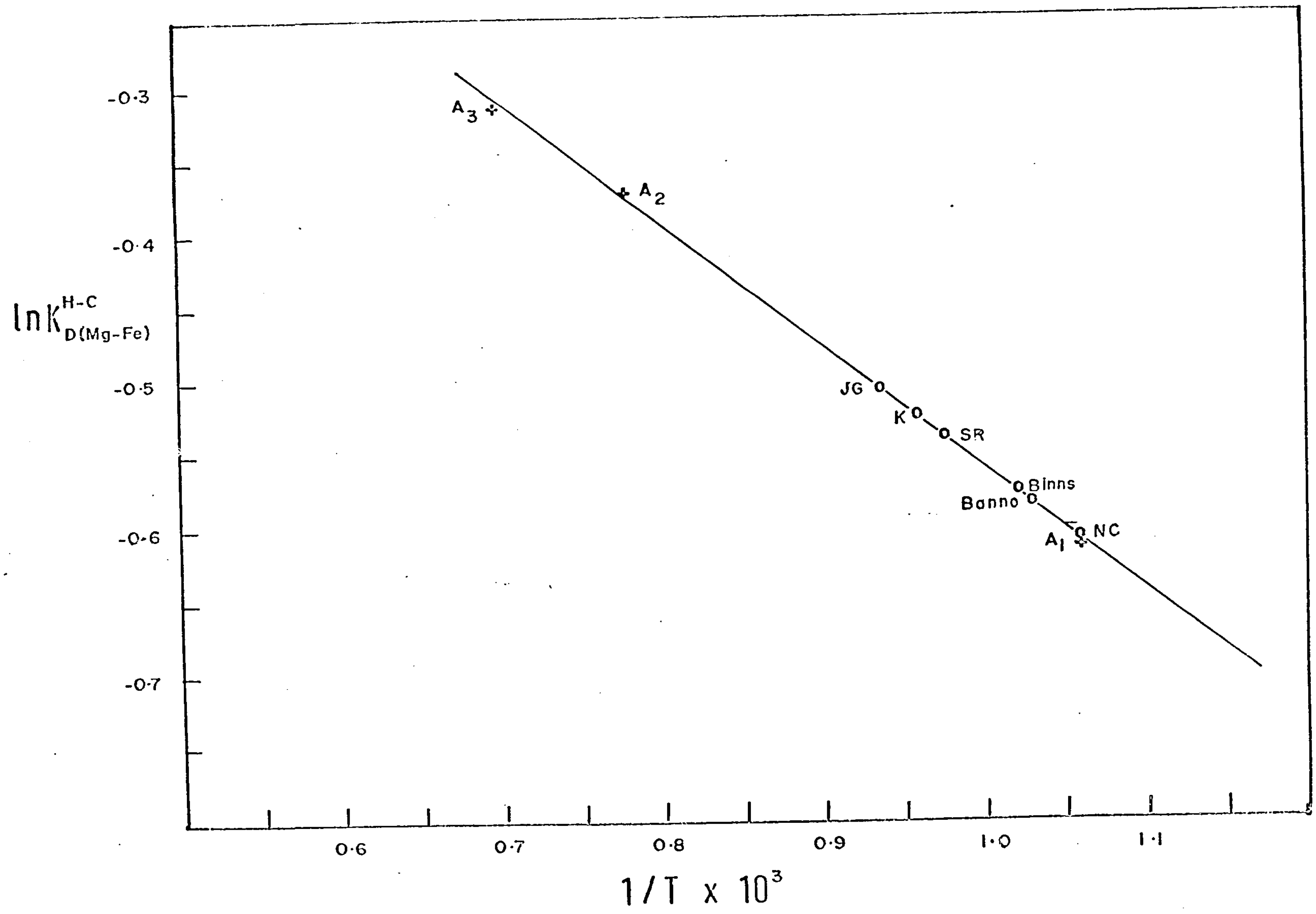


Figure 10: $\ln K_{D(Mg-Fe)}$ vs. 1/T (Kretz, 1963) with other rock groups added.

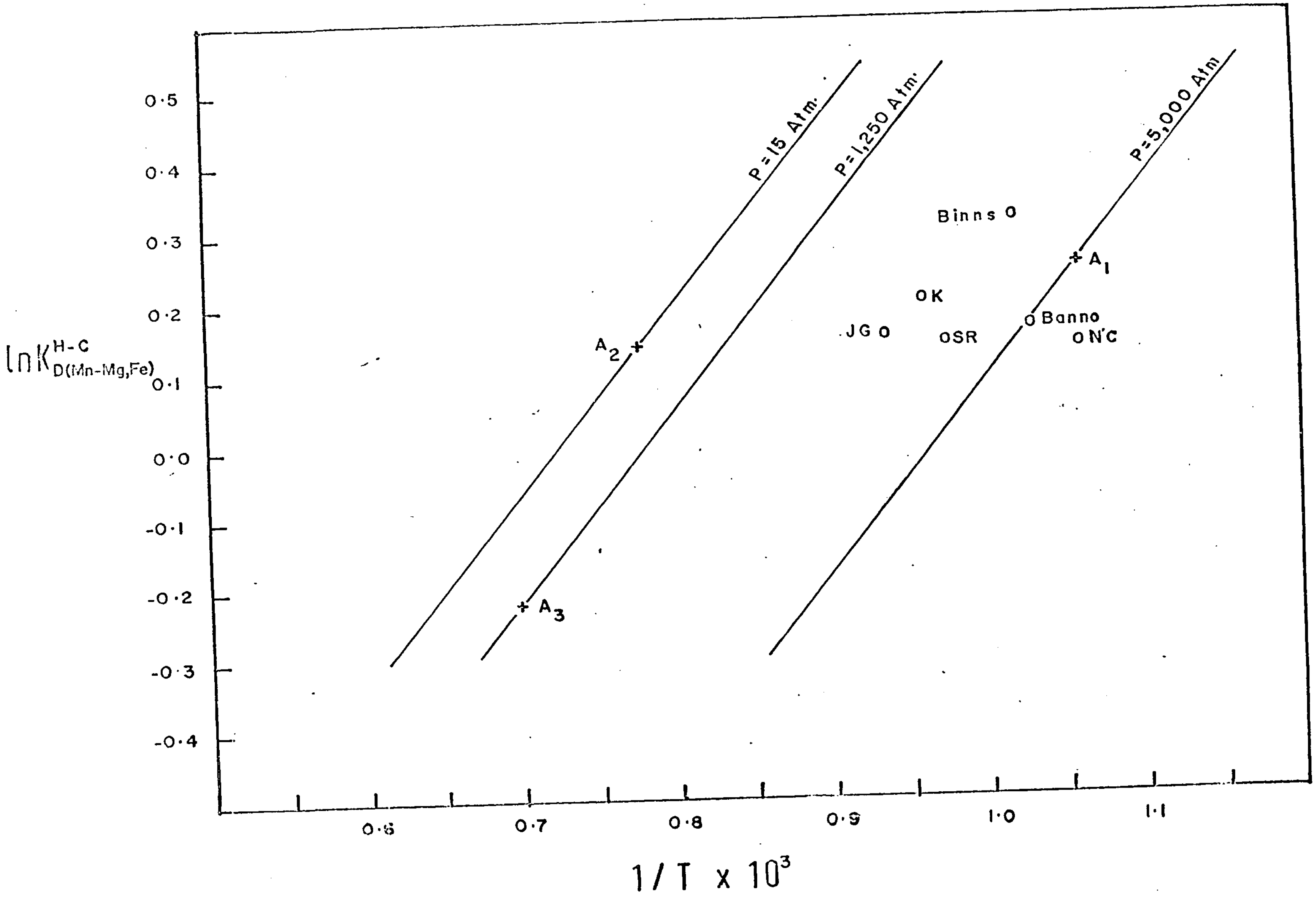


Figure 11: Values for $\ln K_{D(Mn-Mg,Fe)}$ based on the data in Table 2. Data for A_n values obtained from Kretz, 1963.

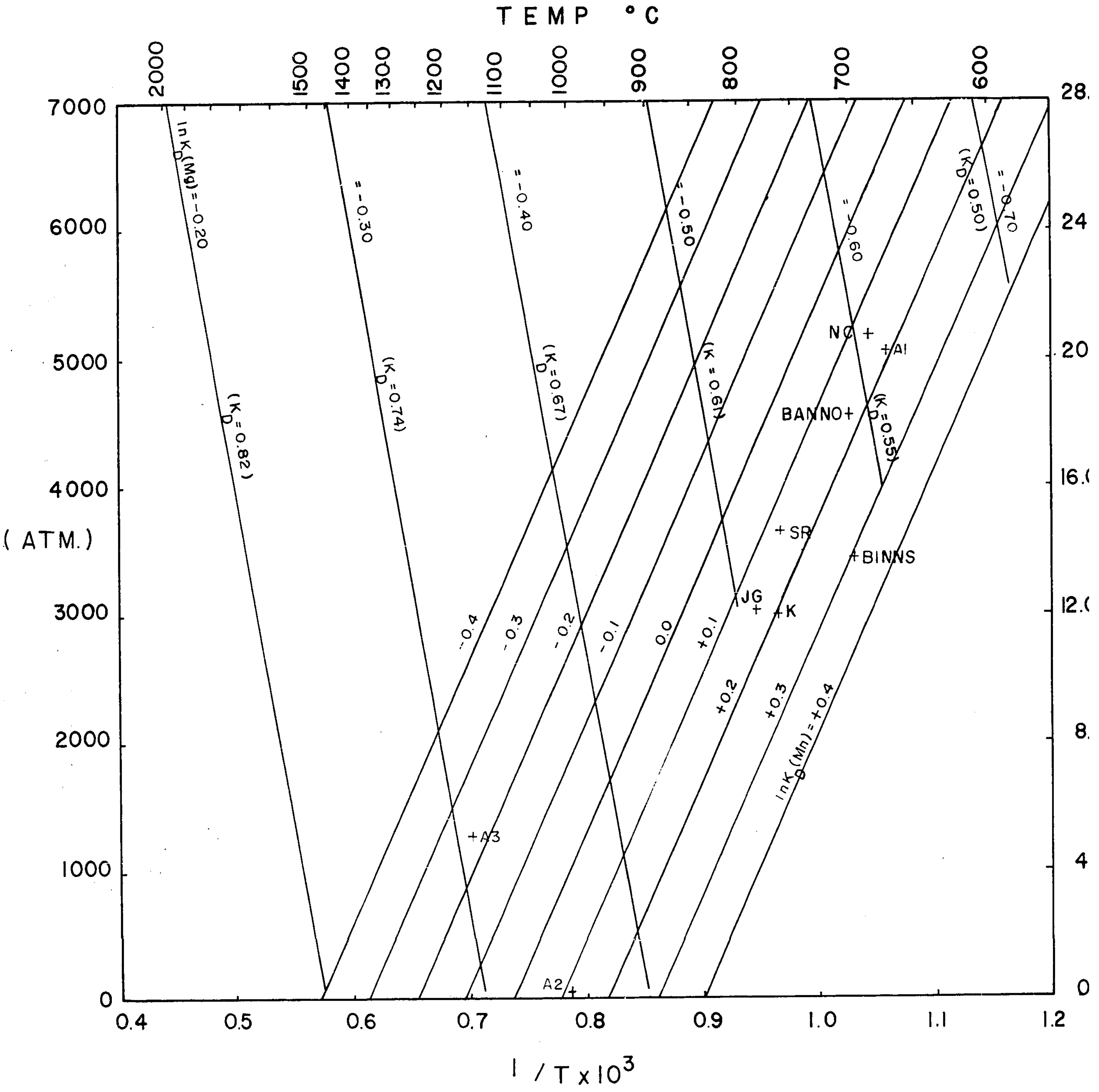


FIGURE 12, TENTATIVE EQUILIBRIUM DIAGRAM RELATING THE DISTRIBUTION COEFFICIENTS WITH REFERENCE TO COEXISTING PYROXENE PHASES (KD(Mg-Fe)),(KD(Mn-Mg,Fe)), ABSOLUTE TEMPERATURE (T), AND PRESSURE (P). MODIFIED FROM KRETZ, 1963.

CONCLUSIONS

(1) The distribution coefficient for Mg-Fe exchange in coexisting pyroxenes was found to differ from ideality and indications are that orthopyroxene is the phase behaving non-ideally. This conclusion is different from that reached by Mueller (1961) and Kretz (1963).

(2) The distribution coefficient of manganese between coexisting pyroxene approached ideality with increasing temperature and decreasing pressure.

(3) Inconclusive evidence indicated that a possible exchange equilibrium for trivalent iron could be established with titanium if titanium is assumed to be in the trivalent state in pyroxenes. No apparent exchange equilibrium is established between trivalent elements and bivalent elements.

(4) Calcium was found not to be involved in an exchange equilibrium with other bivalent elements.

(5) A tentative geothermometer based on Kretz' (1963) work was established and provides information as to the temperature and pressure at which rocks containing coexisting pyroxene reached equilibrium. This geothermometer can be applied provided the distribution coefficients for magnesium $K_{D(Mg-Fe)}$ and for manganese $K_{D(Mn-Mg,Fe)}$ are known.

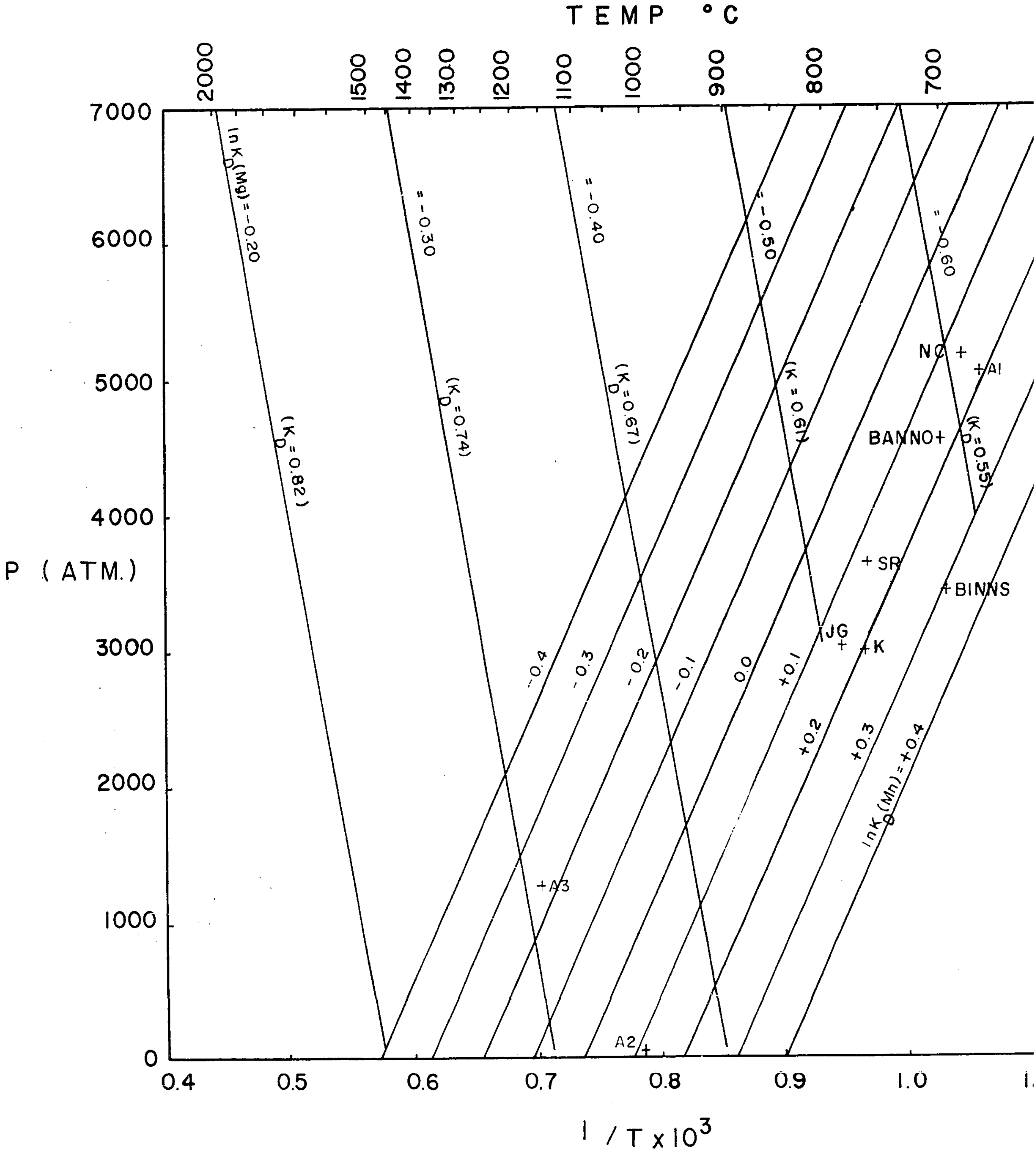
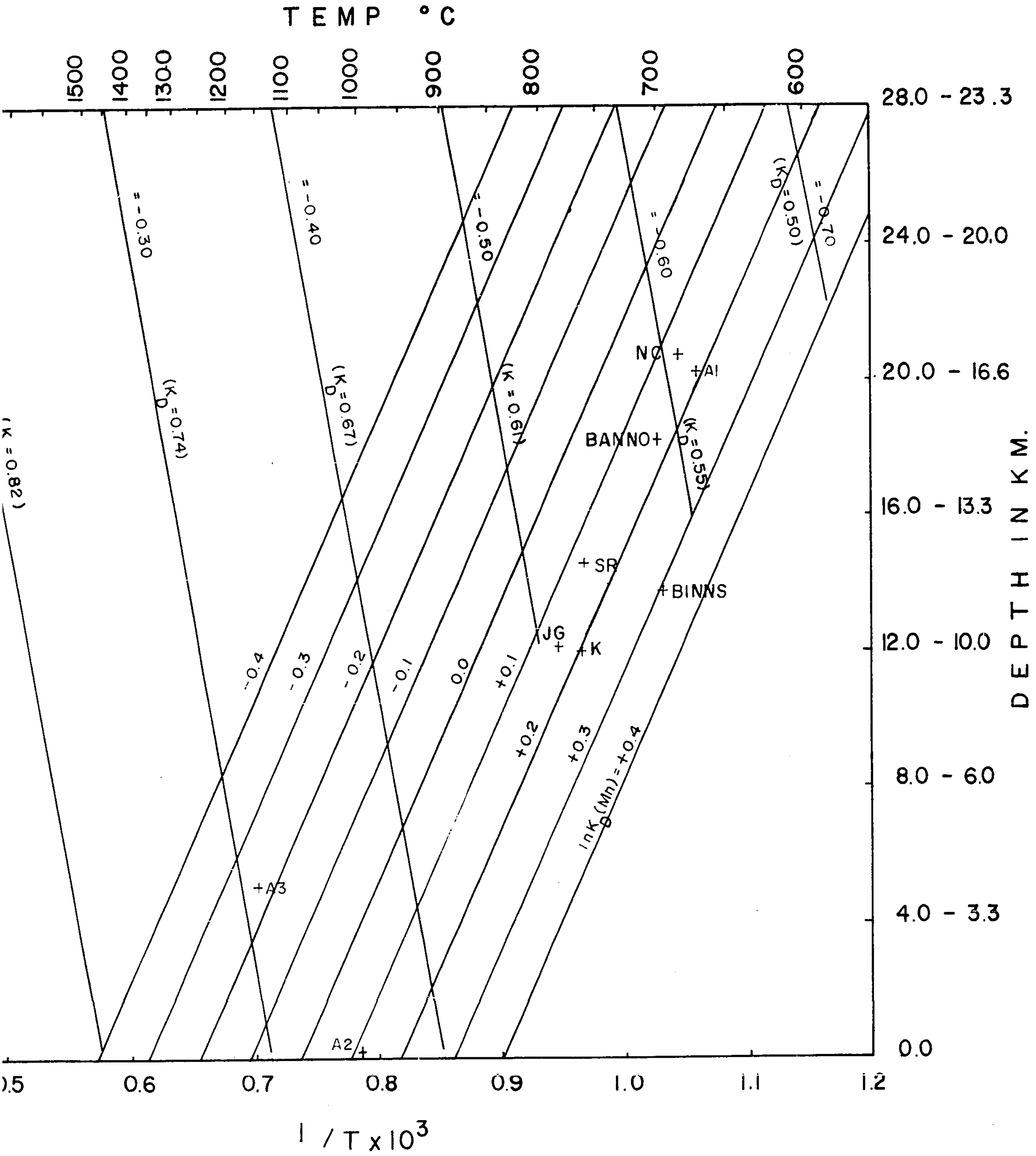


FIGURE 12, TENTATIVE EQUILIBRIUM DIAGRAM RELATING THE DISTRIBUTION COEFFICIE
REFERENCE TO COEXISTING PYROXENE PHASES (KD(Mg-Fe)),(KD(Mn-Mg
ABSOLUTE TEMPERATURE(T), AND PRESSURE(P). MODIFIED FROM KRETZ,



TENTATIVE EQUILIBRIUM DIAGRAM RELATING THE DISTRIBUTION COEFFICIENTS WITH REFERENCE TO COEXISTING PYROXENE PHASES (KD(Mg-Fe)), (KD(Mn-Mg,Fe)), ABSOLUTE TEMPERATURE (T), AND PRESSURE (P). MODIFIED FROM KRETZ, 1963.

The range and possible temperatures and pressures for coexisting pyroxenes in granulitic rocks is approximately established, using this geothermometer, between 680° C at pressure of 5200 Atm. for rock analyses published by Norton and Clavan 1959, and of 760° C with P = 3,000 Atm. for rocks studied by Krank 1951.

Rocks studied by the author give a tentative value of 785° C with a corresponding pressure of 3,050 Atm.

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APPENDIX A

MINERAL SEPARATION TECHNIQUE

MINERAL SEPARATION TECHNIQUE

Rock samples were initially broken to +5 to - 5/8 mesh fraction using a Bico Jaw Crusher, the finer grained portion being rejected to avoid contamination. Final crushing was effected by a Bico Rotary Mill with ceramic plates, followed by a screening to obtain four fractions, +60 mesh, -60 to +170 mesh, -170 to +250 mesh and -250 mesh, of which the second and third fractions were retained for the separation of pyroxenes.

Magnetite, which was present in all samples, was removed using a hand magnet and a Franz Isodynamic Separator at low amperage. A primary separation into mafic and salic minerals was effected with the magnetic separator. Separation of a two-pyroxene concentrate from other mafic minerals, mostly biotite and hornblende, involved one of two procedures. (1) Biotite-free and biotite poor samples (Nos. 1, 8, 94, 125) were mixed with the heavy liquids bromoform (S.G. - 2.8) to remove all remaining salic minerals, and methylene iodide (S.G. = 3.3) to remove hornblende. (2) Samples containing biotite (Nos. 34, 36, 56) were first treated in an elutriator (Frost, 1959) using a slightly acid water solution (1 ml concentrated HCL/5 litres water) to float the biotite and the remaining salic minerals. The slight acidity was necessary to reduce the surface electrostatic charge of the mica plates which tended to ball together with other minerals. A stronger acid solution was avoided to prevent the leaching of metallic ions from the pyroxenes. Final separation was attained on the Franz Isodynamic Separator.

A surface coating of iron oxide was present on some of the mineral grains of the pyroxene concentrates (IH, XC, 34C, 36H, 94C, 125H, 125C). This "Iron Stain" was removed without the leaching of iron from the pyroxenes, using a special procedure based on a method developed by D. E. Coffin (1963) of the Canada Department of Agriculture, for the extraction of free iron and hematite from soils. This method, which is applicable to all silicates except the clay mineral nontronite, is outlined below.

Add 10 millilitres of a citrate buffer (0.15 M with respect to sodium citrate and 0.05 M to citric acid) to a sample of pyroxene (0.5 gram or less) in a 15 millilitre test-tube. Add 0.5 gram sodium hydrosulphite (sodium dithionite). Stopper and shake mechanically in a water bath at 50° C for 30 minutes or for 10 minutes after the sample appears clean. Filter off the resultant liquid, and dry the mineral concentrate.

The concentrates were submitted to Edward L.P. Mercy of the Grant Institute of Geology, University of Edinburgh, for quantitative analysis of the oxides, CaO, FeO, Fe_2O_3, MnO, TiO_2.

APPENDIX B

ROCK DESCRIPTIONS

Specimen #43 (plate 1)

Name: Orthopyroxene-garnet-biotite-plagioclase-sapphirine gneiss.

Texture: This is a porphyroblastic granular rock with a weak foliation defined by biotite. The porphyroblasts are poikilitic garnets.

Mineral Description

1) Orthopyroxene: (31.7%)[1] $2V_x = 60°$

Pleochroism: z = light green

y = pink

x = reddish pink

2) Garnet: (15.6%) This mineral is poikilitic with inclusions of orthopyroxene, biotite and sapphirine.

3) Biotite: (16.5%)

4) Plagioclase: (25.5%) $2V_x$ approximately 90°

$z \wedge 010 = 80°$

$z \wedge 001 = 14°$

An_{25-30} Oligoclase

5) Sapphirine (8.8%) $2V_x = 40°$

Pleochroism: x = pink

y = blue

z = sapphire blue

X-Ray diffraction data on Table 1.

This mineral appears to be an alteration of orthopyroxene.

---

[1] Modal analysis based on 1000 points.

6) Chlorite: (tr)

7) Calcic pyroxene: (tr)

The X-Ray photographs were taken under the following conditions:

A) A 90 mm camera was used.

B) Radiation was Cu K_a with a Ni filter.

C) A very small sample was used which resulted in a "spotty photograph".

D) No correction was made for film shrinkage.

E) First lines are missing due to fogging of the film from long exposure.

X-RAY DIFFRACTION DATA - SAPPHIRINE
Table 1
From Hudson and Wilson, 1966

Fiskernaes (Greenland)		Quairading W. Australia		Strangeways C. Australia		Somerset Island E. Stanwell-Fletcher Lake[1]	
dÅ	I/I$_1$	dÅ	I/I$_1$	dÅ	I/I$_1$	dÅ	I/I$_1$
		7.75	40	7.78	30		
		7.20	30	7.20	20		
				6.10	10		
		5.38	40	5.38	20		
		4.59	40	4.59	30		
4.10	10	4.13	10				
		4.05	50	4.06	30		
		3.85	10	3.87	10		
3.56	20	3.61	50	3.60	20		
		3.50	10	3.48	5		
		3.43	20				
		3.39	20	3.34	5		
3.26	10	3.27	50	3.272	40		
				3.159	20	3.175	10
3.07	10	3.090	40	3.094	20		
2.97	70	3.002	80	2.996	65	2.936	20
2.83	40	2.841	80	2.842	65	2.857	80
2.75	20	2.767	60	2.764	20		
2.68	10	2.700	40	2.700	10		

---

[1] CuK$_\alpha$ radiation with Ni Filter

Fiskernaes (Greenland)		**Quairading W. Australia**		**Strangeways C. Australia**		**Somerset Island E. Stanwell-- Fletcher Lake**	
dÅ	I/I_1	dÅ	I/I_1	dÅ	I/I_1	dÅ	I/I_1
2.63	10	2.652	20	2.650	10		
2.56	30	2.574	60	2.579	30		
2.52	10	2.535	20				
				2.515	5		
		2.486	10				
2.44	60	2.453	100	2.453	100	2.485	100
2.38	10	2.389	40	2.391	5	2.365	15
2.35	30	2.350	80	2.348	60		
		2.292	10				
		2.247	10	2.247	5		
2.21	10	2.210	10	2.215	5		
		2.159	10			2.146	5
2.12	20	2.130	60	2.129	30		
						2.085	5
2.06	20	2.071	40	2.070	40		
		2.027	70			2.027	20
2.01	100	2.017	90	2.019	20		
		1.975	10				
1.95	10			1.953	20		
1.89	20	1.897	60	1.897	30		
		1.881	10				
		1.836	10				
1.82	10	1.824	20	1.823	10		
		1.789	2	1.788	5		

Fiskernaes (Greenland)		Quairaiding W. Australia		Strangeways C. Australia		Somerset Island E. Stanwell-Fletcher Lake	
dÅ	I/I_1	dÅ	I/I_1	dÅ	I/I_1	dÅ	I/I_1
1.757	10	1.767	20	1.763	10		
		1.717	10	1.713	5		
1.702	10	1.707	10				
		1.692	10	1.690	5		
		1.664	20	1.663	5		
1.632	10	1.635	20	1.637	5		
		1.622	20	1.623	10		
1.594	10	1.597	20	1.595	5		
1.574	20	1.578	20	1.579	10		
1.549	50	1.555	50	1.552	10		
1.538	40	1.542	50	1.543	25		
		1.532	5	1.530	5	1.534	35
				1.516	5		
1.488	10			1.487	10	1.494	25
				1.463	5		
1.438	90	1.439	90	1.441	80	1.452	80
1.420	60	1.422	90	1.422	70	1.432	80
1.408	30	1.411	60	1.410	60		
1.382	10			1.389	5		
				1.375	5		
1.355	20	1.359	20	1.358	10		
		1.347	20	1.348	10		

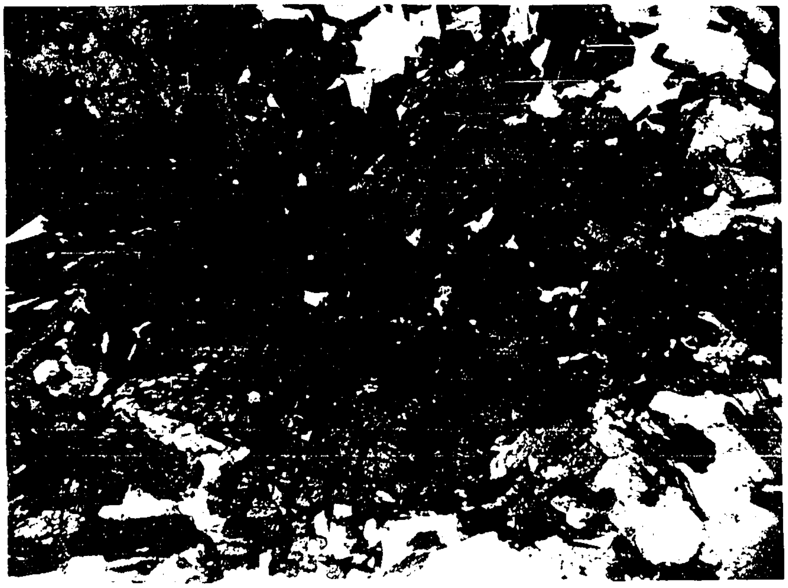

Plate 1: Photomicrograph of sapphirine-bearing rock. The sapphirine is the dark blue mineral associated with orthopyroxene, biotite, plagioclase and garnet. Magnification 50X Ordinary light.

Specimen #1 (plates 2 & 3)

Name: Hornblende-calcic pyroxene-orthopyroxene-quartz-plagioclase.

Texture: The rock is a weakly foliated, medium-grained allotriomorphic granulitic rock.

Mineral Description

1) Quartz: (25.8%)[1] All grains are strained.

2) Hornblende: (2.8%) $2V_x = 60°$

Dispersion $v > r$,

Pleochroism z = bluish green

y = brownish green

x = very light brown

3) Orthopyroxene[2]: (7.4%) $2V_x = 53°$

Pleochroism =z = green

y = pink

x = pink

4) Calcic pyroxene: (11.8%) $2V_z = 54°$

x = green

y = slightly yellow green

z = light green

5) Biotite: (tr) The biotite is strongly pleochroic, generally surrounded by opaques or other mafics.

---

[1] Modal analysis based on 500 points.

[2] The 2V of orthopyroxene and calcic pyroxene in specimens 1,8,34,36,56,94,125 were determined by universal stage.

6) Plagioclase[3]: (50.0%) $2V_x = 70°$, $z \wedge 010 = 65°$.

$z \wedge 001 = 21°$.

Composition: An_{45} = Andesine.

A polysynthetic albite twin is present.

A second twin law is also present.

---

3. Plagioclase optical properties in all specimens were determined on a flat stage. Composition was determined by measurements in a section perpendicular to the acute or obtuse bisectrix figure.

Plate 2: Photomicrograph of specimen 1 showing orthopyroxene in physical contact with calcic pyroxene. Under plane light.
Scale 1 cm = 0.96 mm.

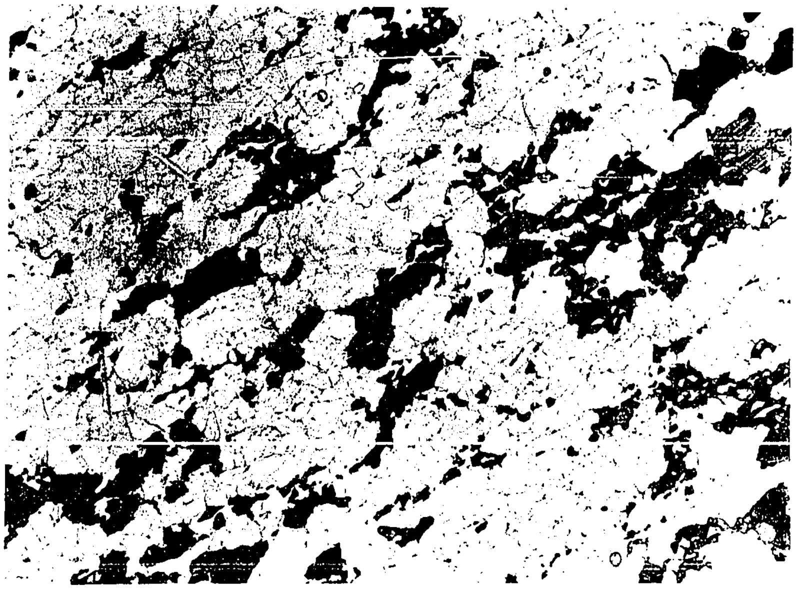

Plate 3: Photomicrograph of specimen 1 showing the mineral association within the rock. Plain light. Magnification 8x.

Specimen #8 (plates 4,5)

Name: Clinopyroxene-orthopyroxene-quartz-plagioclase gneiss.

Texture: The texture is porphyroblastic-granular with metacrysts of quartz. The groundmass has granoblastic texture with grains of feldspar, hypersthene and augite.

Mineral Description

1) Apatite: (tr)[1] This occurs as random grains in the felsic minerals.

2) Quartz: (28.2%) Quartz occurs in long stringers.

3) Plagioclase: (64.0%) The albite twinning shows undular extinction.

Extinction: $z \wedge 010 = 68°$

$z \wedge 001 = 25°$

Composition: An_{40} = Andesine

Note: There is an alteration of plagioclase to sericite.

4) Calcic pyroxene: (0.5%) This mineral occurs as random, irregularly shaped grains in association with orthopyroxene and magnetite.

---

1. Modal analysis based on 836 points.

Pleochroism:

x = green

y = slightly yellow-green

z = green

$2V_z$ = 54°

5) **Orthopyroxene:** (3.4%) This mineral has an occurrence similar to that of augite $2V_x$ = 64°.

Pleochroism: z = green

x = pink

y = pink

6) **Magnetite:** (3.5%)

7) **Biotite:** (tr) Biotite is associated with magnetite.

8) **Hornblende:** (0.7%) This mineral occurs in too small a quantity in order to determine the optical properties.

9) **Hematite:** (tr)

10) **Chlorite:** (tr) Minor alteration of biotite.

Plate 4: Photomicrograph of specimen 8 showing orthopyroxene in physical contact with calcic pyroxene. Under plane light.
Scale 1 cm = 0.96 mm.
Magnification 104x.

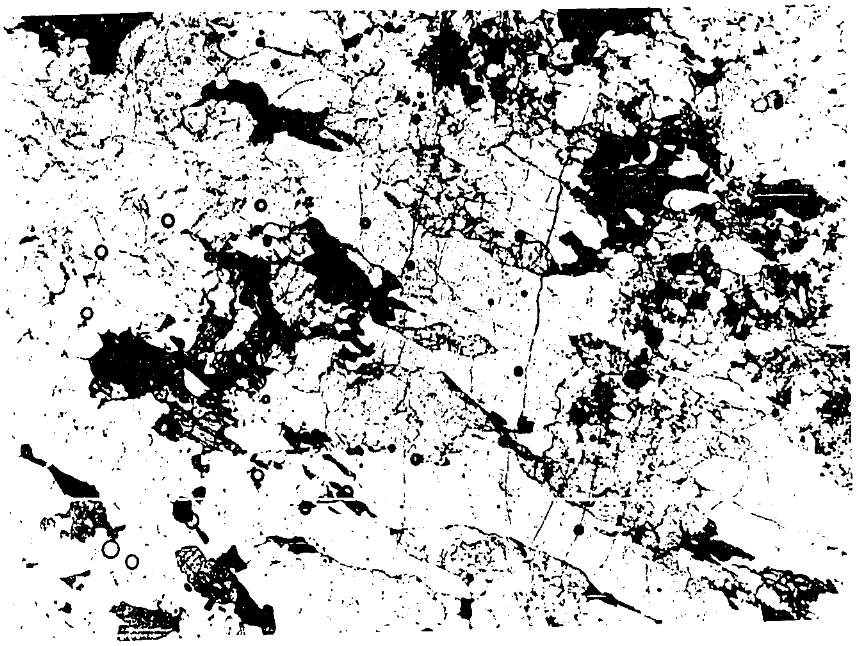

Plate 5: Photomicrograph of specimen 8 showing the mineral association within the rock. Plain light.
Magnification 8x.

Specimen #34 (plates 6,7)

Name: Orthopyroxene-clinopyroxene-plagioclase gneiss.

Texture: This rock has a granular texture with a very weak foliation as shown by the elongation of a few grains. The grains are equant.

Mineral Description:

1) Orthopyroxene: (17.6%)[1] There is a slight chloritic alteration on a few grains.

$2V_x = 55°$

Pleochroism: z = green

x = dark pink

y = lighter pink

2) Calcic Pyroxene: (17.6%) $2V_z = 64°$

Weak Pleochroism: x = green

z = green

y = slightly yellow green

3) Plagioclase: (59.2%) Polysynthetic albite twinning is present.

2V is very large, approaching 90°.

$z \wedge 001 = 45°$

$z \wedge 010 = 70°$

Composition: An_{50} = Andesine-Labradorite.

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[1] Modal analysis based on 631 points.

4) Quartz: (4.9%) There is a small amount of quartz and it occurs in lens-shaped grains with filiform inclusions which are non-parallel to the extinction of the quartz grains.

5) Hornblende (tr).

6) Magnetite: (2.4%) This is associated with the mafic minerals.

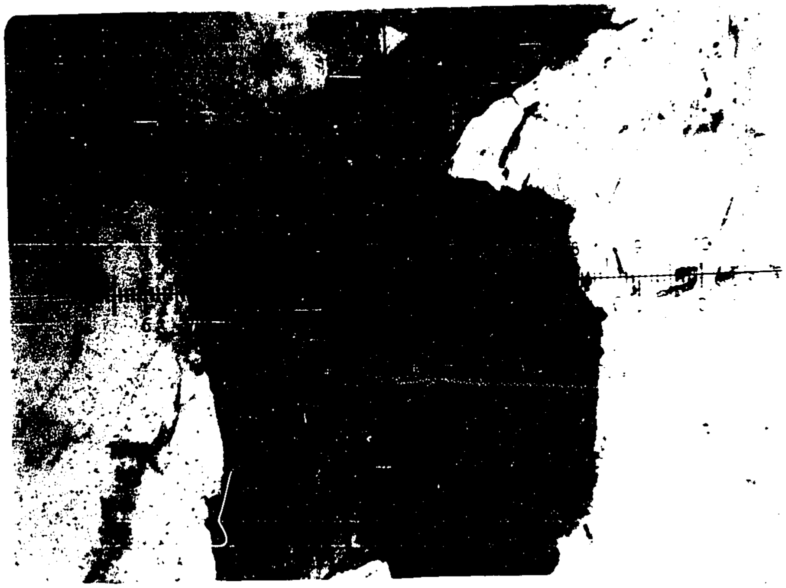

Plate 6: Photomicrograph of specimen 34 showing orthopyroxene in physical contact with calcic pyroxene. Under plane light. Scale 1 cm = 0.96 mm. Magnification 104x.

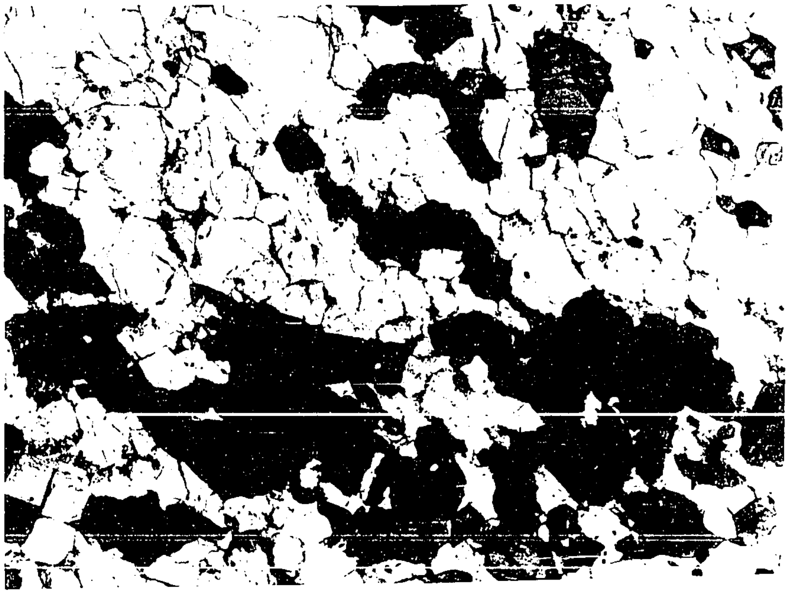

Plate 7: Photomicrograph of specimen 34 showing the mineral association within the rock. Plain light. Magnification 8x.

Specimen #36 (plates 8,9)

Name: Orthopyroxene-clinopyroxene-plagioclase gneiss.

Texture: The rock is granular with a very weak foliation, and has a medium grain size.

Mineral Description:

1) **Biotite:** (tr)[1] The biotite shows a red-brown to clear yellow pleochroism. $2V_z = 50°$.

2) **Calcic Pyroxene:** (16.3%) This mineral occurs as independent grains and in association with orthopyroxene.

$2V_z = 53°$.

Pleochroism: x = green
z = green
y = slightly yellow green

3) **Orthopyroxene:** (11.1%) $2V_x = 60°$.

There is some alteration of orthopyroxene to chlorite.

Pleochroism: z = green
x = pink
y = lighter yellowish pink

4) **Apatite:** (tr) This mineral occurs in a random distribution.

5) **Magnetite:** (3.6%).

---

[1] Modal analysis based on 726 points.

6) **Plagioclase:** (68.0%) $2V_z = 70°$.

$z \wedge 010 = 77°$

$z \wedge 001 = 15°$

An_{30} = Oligoclase

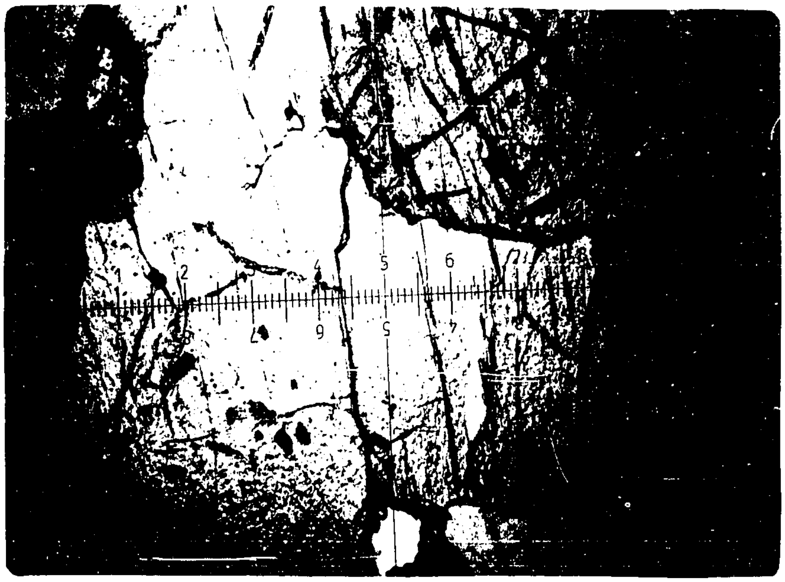

Plate 8: Photomicrograph of specimen 36
showing orthopyroxene in physical
contact with calcic pyroxene.
Under plane light.
Scale 1 cm = 0.96 mm.
Magnification 104x.

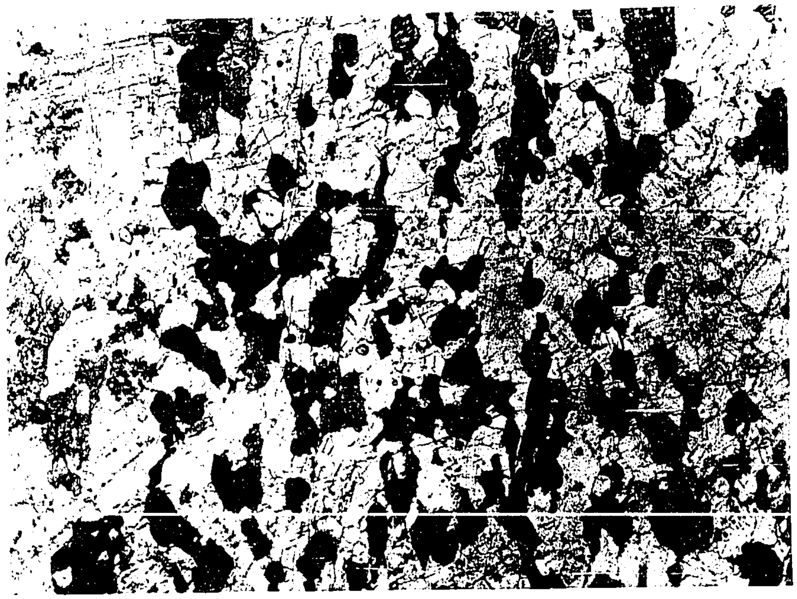

Plate 9: Photomicrograph of specimen 36
showing the mineral association
within the rock. Plain light.
Magnification 8x.

Specimen #56 (plates 10, 11)

Name: Biotite-orthopyroxene-clinopyroxene-plagioclase gneiss.

Texture: This rock has a lepidoblastic to granular texture with the foliation defined by the orientation of biotite flakes. Medium grain size.

Mineral Description:

1) Biotite: (23.2%)[1]

2) Calcic Pyroxene: (16.2%) $2V_z = 56°$.

Pleochroism: x = green

z = green

y = slight yellow-green

3) Orthopyroxene: (11.5%) $2V_x = 60°$.

Pleochroism: z = green

x = pink

y = lighter yellow-green

4) Plagioclase: (47.4%) $z \wedge 010 = 77°$

$z \wedge 001 = 30°$

$2V_x = 90°$

Composition: An_{40} = Andesine

5) Apatite: (tr).

6) Magnetite: (0.2%).

---

[1] Modal analysis based on 475 points.

Plate 10: Photomicrograph of specimen 56 showing orthopyroxene in physical contact with calcic pyroxene. Under plane light. Scale 1 cm = 0.96 mm. Magnification 104x.

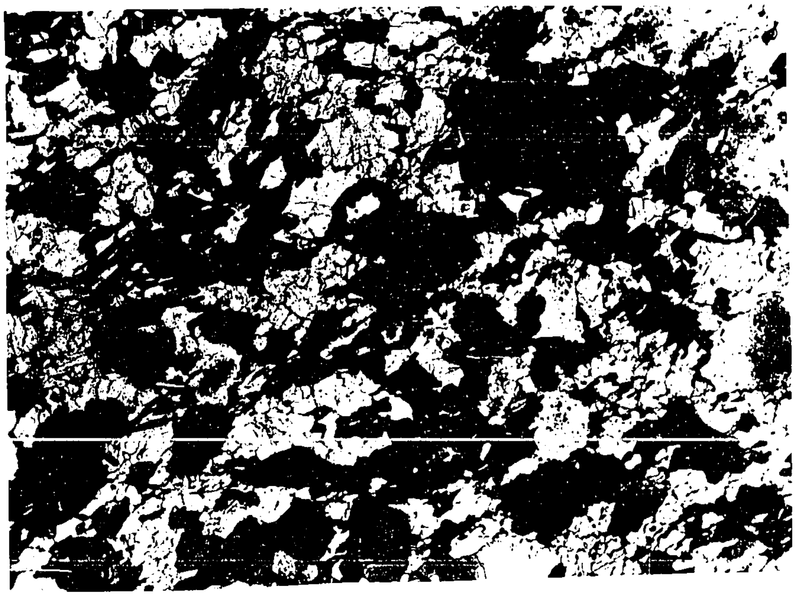

Plate 11: Photomicrograph of specimen 56 showing the mineral association within the rock. Plain light. Magnification 8x.

Specimen #94 (plates 12, 13)

Name: Hornblende-orthopyroxene-clinopyroxene-plagioclase gneiss.

Texture: This rock has a granular texture with little foliation visible in thin section. All grains are equant and panidiomorphic. Grain size: medium.

Mineral Description:

1) **Plagioclase:** (49.9%)[1] $2V_x = 90°$.

$z \wedge 010 = 60°$.

$z \wedge 001 = 40°$.

Composition: An_{55} = Labradorite.

2) **Magnetite: Ilmenite:** (8.5%).

3) **Orthopyroxene:** (9.0%) $2V_x = 60°$.

Pleochroism:
z = green
x = pink
y = a greenish pink

(almost no colour change) (or to yellowish).

4) **Calcic Pyroxene:** (23.7%) Probably augite $2V_z = 60°$.

Pleochroism:
z = green
x = green
y = slightly yellow green

---

[1] Modal analysis based on 785 points.

5) Hornblende: (6.2%)

Pleochroism: x = light yellow brown
y = brown
z = brown

6) Potash Feldspar: (2.7%) It was not possible to determine the type. It is probably microcline.

Plate 12: Photomicrograph of specimen 94 showing orthopyroxene in physical contact with calcic pyroxene.
Under plane light.
Scale 1 cm = 0.96 mm.
Magnification 104x.

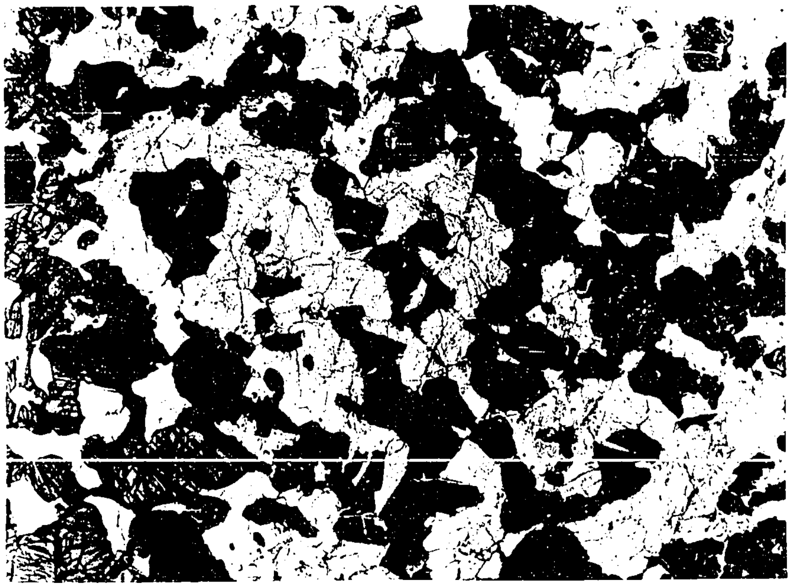

Plate 13: Photomicrograph of specimen 94 showing the mineral association within the rock. Plain light.
Magnification [illegible]x.

Specimen #125 (plates 14, 15)

Name: Plagioclase-orthopyroxene-clinopyroxene gneiss.

Texture: Granular texture, with a slight preferred orientation, all grains anhedral. Medium grain size.

Mineral Description:

1) Plagioclase: (73.3%)[1] 2V = 90°.
$z \wedge 010 = 69°$.
$z \wedge 001 = 26°$.

Composition: An_{40} = Andesine.

Note: The feldspar is altered in part to sericite.

2) Orthopyroxene: (7.7%).

Pleochroism: x = pink
y = yellow pink
z = green

$2V_x = 50°$.

3) Calcic pyroxene: (16.6%).

Slight Pleochroism:
y = slight yellow-green
x = darker green
z = lighter green
$2V_z = 58°$.

Note: Orthopyroxene seems to have grown around one of the grains of clinopyroxene, though a side-by-side relationship is more common.

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[1] Modal analysis based on 777 points.

4) Magnetite-ilmenite (magnetic) (2.7%).

5) Apatite (tr).

Plate 14: Photomicrograph of specimen 125 showing orthopyroxene in physical contact with calcic pyroxene. Under plane light. Scale 1 cm = 0.96 mm. Magnification 104x.

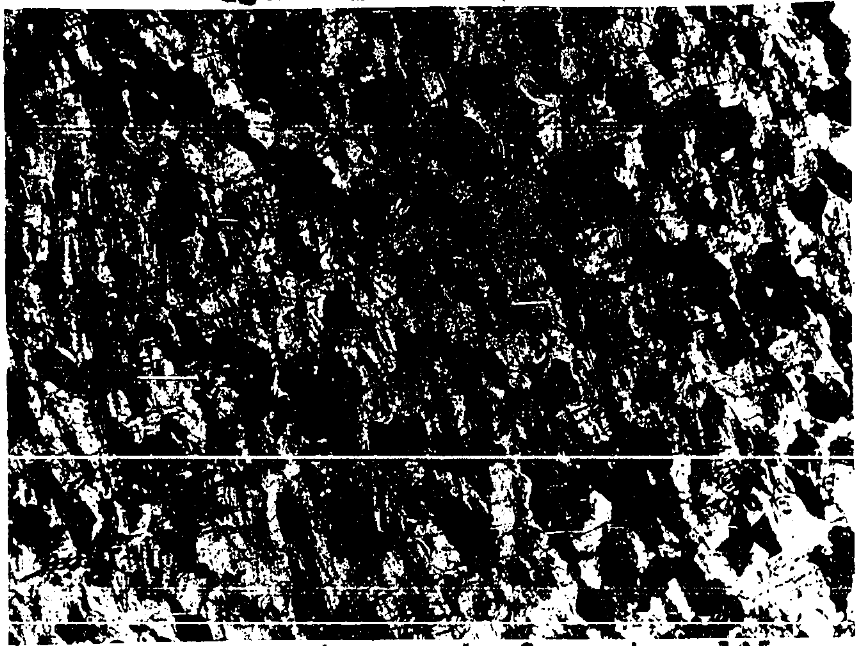


Plate 15: Photomicrograph of specimen 125 showing the mineral association within the rock. Plain light. Magnification 8x.

APPENDIX C

PARTIAL PYROXENE ANALYSES

PARTIAL PYROXENE ANALYSES

Ref. No.	Sample No.	CaO	MgO	FeO	Fe_2O_3	MnO	TiO_2
1H	1H	1.6	14.4	N.D.	30.7*	0.76	0.54
1C	1C	17.9	11.6	N.D.	14.0*	0.39	0.32
2H	8H	3.10	15.70	24.61	1.35	0.96	0.27
2C	8C	20.32	11.42	11.57	0.75	0.50	0.25
3H	34H	2.33	14.60	26.49	1.43	0.64	0.15
3C	34C	20.69	10.90	11.44	1.51	0.32	0.26
4H	36H	3.77	18.56	20.02	0.40	0.56	0.66
4C	36C	21.02	12.73	8.37	1.75	0.30	0.26
5H	56H	3.18	19.68	20.50	1.35	0.59	0.06
5C	56C	20.81	12.81	7.59	1.67	0.27	0.19
6H	94H	1.93	17.88	24.69	1.37	0.66	0.20
6C	94C	21.50	12.15	9.66	1.41	0.30	0.39
7H	135H	4.7	13.9	N.D.	28.4*	0.40	1.00
7C	135C	18.37	10.55	N.D.	14.34*	0.23	0.26

Somerset Island - J. F. Giguere, 1966.

H = orthopyroxene.

C = clinopyroxene.

Analysis by Edward L. P. Mercy of the Grant Institute of Geology, University of Edinburgh.

* Total iron.
N.D. Not determined.

PARTIAL PYROXENE ANALYSES

Ref. No.	Author's No.	CaO	MgO	FeO	Fe_2O_3	MnO	TiO_2	
8H	A - 12	1.2	26.9	13.7	1.4	0.23	N.D.	QUEBEC - KRANCK, 1951
8C		22.88	16.8	3.8	1.4	0.11		
9H	B1 - 3	2.2	13.1	31.8	2.4	0.37	N.D.	
9C		21.0	9.6	15.2	2.00	0.18		
10H	B1 - 6	1.7	9.0	36.6	2.3	1.14	N.D.	
10C		21.2	7.7	17.1	1.9	0.57		
11H	B1 - 21	1.7	9.8	35.9	3.1	0.14	N.D.	
11C		21.0	7.7	17.4	1.9	0.06		
12H	A - 50	1.6	3.4	40.1	4.1	3.1	N.D.	
12C		15.3	1.8	17.9	9.6	2.03		
13H	M - 4	1.74	6.67	40.4	2.3	0.52	N.D.	
13C		19.3	6.0	19.9	2.7	0.26		
14H	H - 7	1.2	7.1	39.5	1.9	1.51	N.D.	
14C		19.5	5.8	19.6	2.8	0.74		
15H	H - 9	1.3	7.6	38.8	1.7	1.61	N.D.	
15C		19.6	6.6	19.4	2.1	0.75		
16H	X - 819	1.58	28.70	9.28	1.85	0.21	0.25	SCOURIE SUTHERLAND - O'HARA, 1961
16C		22.29	13.77	4.55	2.75	0.30	0.84	

Ref. No.	Author's No.	CaO	MgO	FeO	Fe_2O_3	MnO	TiO_2	
17H	X - 646	0.12	23.32	19.57	3.56	0.30	0.06	
17C		20.82	12.52	8.32	2.31	0.19	0.55	SCOURIE SUTHERLAND - O'HARA, 1961 (Con't.)
18H	X - 291	1.84	17.60	24.86	1.69	0.56	0.13	
18C		19.89	11.74	9.99	1.79	0.23	0.56	
19H	S - 5	0.60	19.52	22.53	2.97	0.70	0.13	
19C		20.82	12.40	8.07	2.61	0.29	0.58	SCOURIE SUTHERLAND -
20H	0 - 0	1.44	15.78	27.85	2.34	0.85	0.64	MUIR & TILLEY, 1958
20C		20.82	12.00	12.30	1.00	0.41	0.42	OSLO, NORWAY
21H	R - 62	0.53	30.31	9.07	1.54	0.25	0.19	
21C		23.61	16.40	2.12	1.98	0.11	0.69	RODIS, SOUTH HARRIS, SCOTLAND, 1964
22H		2.29	10.77	33.67	1.23	0.67	0.40	
22C		18.66	8.60	16.60	2.95	0.28	0.16	HITTERO, NORWAY, 1964
23H	3709	0.06	26.65	15.28	1.38	0.28	0.10	MADRAS, INDIA, 1955
23C		23.67	14.18	4.48	1.85	0.08	0.68	(ALL ANALYSES BY HOWIE)
24H	4645	0.50	25.74	16.51	0.55	0.27	0.15	
24C		23.51	14.42	4.70	1.99	0.13	0.72	
25H	2270	0.90	20.75	23.01	0.59	0.87	0.15	
25C		21.46	13.48	7.94	2.35	0.25	0.24	
26H	2941	0.70	17.67	26.51	1.92	0.32	0.30	
26C		19.66	11.59	9.76	2.58	0.20	0.70	
27H	4642	0.16	13.74	32.60	1.31	0.59	0.11	
27C		20.11	10.51	14.09	1.32	0.24	0.30	

Ref. No.	Author's No.	CaO	MgO	FeO	Fe_2O_3	MnO	TiO_2	
28H	115	1.57	11.94	34.03	1.60	0.89	1.02	
28C		20.10	8.21	15.05	3.21	0.48	0.85	
29H	84319	0.87	13.51	32.83	0.60	1.26	0.18	BROKEN HILL, N.S.W.
29C		21.28	10.73	13.08	0.75	0.44	0.20	BINNS, 1962
30H	84320	0.82	11.98	36.55	0.09	0.87	0.28	
30C		21.49	9.66	15.67	0.10	0.38	0.25	
31H	84321	1.10	7.63	40.75	0.32	1.64	0.48	
31C		19.09	6.82	21.39	1.28	0.82	0.40	
32H	84322	0.95	17.51	28.22	0.67	0.61	0.29	
32C		21.54	12.70	11.32	0.55	0.26	0.39	
33H	84323	1.36	10.88	36.86	0.57	0.72	0.24	
33C		20.04	8.86	18.21	0.66	0.32	0.39	
34H	84324	0.87	17.28	28.30	0.63	0.80	0.21	
34C		20.90	12.09	11.70	0.63	0.33	0.25	
35H	84325	0.87	15.56	28.34	1.78	2.84	N.D.	
35C		21.30	11.81	11.85	0.26	0.26		
36H	R - 18	0.82	21.39	17.77	1.56	0.16	0.20	DELEGATE, N.S. WALES,
36C		13.45	13.23	6.13	2.18	0.09	0.87	AUSTRALIA
37H	R - 112	0.33	20.43	16.20	6.57	0.47	1.10	LOVERING & WHITE, 1964
37C		22.18	12.03	5.43	1.62	0.14	0.21	

Ref. No.	Author's No.	CaO	MgO	FeO	Fe_2O_3	MnO	TiO_2	
38H	90703	1.31	25.44	16.20	1.14	0.44	0.33	
38C		21.55	15.91	6.40	0.48	0.13	0.29	
39H	90702	1.36	20.74	22.74	1.02	0.63	0.51	LIZARD, CORNWALL, ENGLAND
39C		21.13	14.21	9.11	0.52	0.18	0.62	D. H. GREEN, 1964
40H	90697	1.86	19.15	24.21	0.85	0.76	1.14	
40C		20.71	13.25	10.30	0.70	0.40	0.97	
41H	90696	1.46	19.75	25.75	1.36	0.68	0.25	
41C		18.64	14.58	10.40	2.15	0.19	0.46	

Note: These specimens were rejected because they are contact metamorphic rocks.

42H	35 - 5	0.66	20.29	25.65	1.18	0.75	0.17	PENNSYLVANIA & DELAWARE
42C		21.75	13.11	8.97	1.88	0.35	0.28	
43H	35 - 6	0.87	19.49	26.02	1.44	0.95	0.17	Orthopyroxene: CLAVAN et al,
43C		21.08	12.53	9.31	2.03	0.45	0.27	1954
44H	35 - 8	1.02	20.69	23.60	1.39	0.73	0.18	Clinopyroxene: NORTON &
44C		21.10	13.22	8.05	3.39	0.34	0.28	CLAVAN, 1959
45H	35 - 9	0.75	21.62	22.46	1.34	0.57	0.14	
45C		21.73	13.65	7.28	2.03	0.24	0.31	
46H	35 - 13	1.87	18.00	25.16	1.85	0.38	0.25	
46C		20.55	12.22	9.52	1.40	0.19	0.36	
47H	35 - 19	1.05	24.95	18.65	1.67	0.43	0.09	
47C		22.18	14.83	5.92	1.70	0.19	0.28	

Ref. No.	Author's No.	CaO	MgO	FeO	Fe_2O_3	MnO	TiO_2	
48H	35 - 32	2.17	25.65	17.14	0.95	0.41	0.15	
48C		22.43	15.60	5.87	1.50	0.18	0.40	
49H	G - 8	0.49	23.76	17.09	2.84	0.19	0.19	
49C		20.66	13.44	5.35	2.39	0.11	0.19	GLENELG, SCOTLAND-O'HARA, 1960
50H	5	0.89	22.13	20.89	2.00	0.29	0.49	
50C		20.25	14.49	8.85	1.43	0.21	0.80	
51H	2	1.82	15.36	30.97	0.24	1.40	0.76	LAPLAND - ESKOLA, 1952
51C		20.61	11.02	12.99	2.21	0.48	0.74	
52H	3 - C	0.60	19.51	22.58	2.89	0.70	0.20	
52C		21.17	12.32	8.58	2.60	0.30	0.50	
53H	124	0.95	16.34	20.84	2.35	0.80	0.40	
53C		21.61	12.01	11.61	1.10	0.45	0.45	SALTORA, W. BENGAL, INDIA
54H	10	1.09	15.88	28.09	1.52	0.88	0.25	SEN AND REGE, 1966
54C		20.54	11.57	12.41	1.03	0.50	0.40	
55H	213	0.70	20.84	22.38	0.94	0.60	0.20	
55C		21.56	13.69	8.18	0.83	0.25	0.45	
56H	JARE	0.21	29.28	12.52	2.17	0.47	0.04	
56C	57012501	22.91	17.17	4.33	0.44	0.23	0.11	LUTZOW, HOLM BAY, ANTARTICA
57H	JARE	0.10	17.47	28.54	1.70	0.76	0.19	BANNO et al, 1964
57C	57110802	20.53	12.32	10.55	3.00	0.33	0.25	

APPENDIX D

MOLE FRACTIONS

Sample No.	Ca	Mg	Fe+3	Mn	Ti	
1H	0.0370	0.4816	0.5184*	0.0142	0.0090	
1C	0.4080	0.6214	0.3786*	0.0117	0.0086	
2H	0.0702	0.5320	0.0226	0.0182	0.0046	
2C	0.4492	0.6376	0.0207	0.0156	0.0070	
3H	0.0538	0.4955	0.0239	0.0122	0.0026	
3C	0.4620	0.6294	0.0422	0.0104	0.0075	
4H	0.0834	0.6230	0.0067	0.0106	0.0111	SOMERSET ISLAND - J. F. GIGUERE, 1966
4C	0.4644	0.7305	0.0483	0.0097	0.0075	
5H	0.0683	0.6311	0.0214	0.0106	0.0010	
5C	0.4671	0.7505	0.0471	0.0089	0.0056	
6H	0.0419	0.5634	0.0213	0.0117	0.0032	
6C	0.4680	0.6915	0.0389	0.0096	0.0111	
7H	0.1069	0.4922	0.5078*	0.0080	0.0176	
7C	0.4260	0.5930	0.4070*	0.0073	0.0073	
8H	0.0243	0.7777	0.0200	0.0038	N.D.#	
3C	0.4649	0.8874	0.0360	0.0033		
9H	0.0486	0.4234	0.03770	0.0068	N.D.	QUEBEC - KRANCK, 1951
9C	0.4543	0.5295	0.0528	0.0056		
10H	0.0397	0.3047	0.0378	0.0215	N.D.	
10C	0.4684	0.4452	0.0526	0.0184		

N.D.#: Not determined.

*: Total Iron.

Sample No.	Ca	Mg	Fe^{+3}	Mn	Ti	
11H	0.0392	0.3273	0.0497	0.0027	N.D.	QUEBEC - KRANCK, 1951 (Cont'd.)
11C	0.4636	0.4409	0.0521	0.0019		
12H	0.0425	0.1313	0.0740	0.0637	N.D.	
12C	0.4815	0.1520	0.2904	0.0888		
13H	0.0409	0.2273	0.0381	0.0100	N.D.	
13C	0.4470	0.3495	0.0736	0.0085		
14H	0.0286	0.2426	0.0317	0.0285	N.D.	
14C	0.4549	0.3453	0.0776	0.0244		
15H	0.0308	0.2588	0.0284	0.0302	N.D.	
15C	0.4462	0.3775	0.0572	0.0238		
16H	0.0324	0.8464	0.0268	0.0035	0.0037	SCOURIE SUTHERLAND - O'HARA, 1961
16C	0.4954	0.8436	0.0784	0.0103	0.0253	
17H	0.0025	0.6799	0.0498	0.0049	0.0009	
17C	0.4654	0.7284	0.0635	0.0062	0.0159	
18H	0.0402	0.5579	0.0263	0.0100	0.0021	
18C	0.4518	0.6768	0.0495	0.0075	0.0160	
19H	0.0132	0.6069	0.0445	0.0122	0.0020	SCOURIE SUTHERLAND
19C	0.4692	0.7325	0.0722	0.0096	0.0170	
20H	0.0319	0.5024	0.0363	0.0152	0.0102	OSLO, NORWAY - MUIR & TILLEY, 1958
20C	0.4419	0.6349	0.0260	0.0122	0.0111	

Sample No.	Ca	Mg	Fe^{+3}	Mn	Ti	
21H	0.0106	0.8562	0.0215	0.0040	0.0027	RODIS, SOUTH HARRIS, SCOTLAND, 1964
21C	0.4911	0.9324	0.0538	0.0035	0.0194	
22H	0.0526	0.3631	0.0205	0.0127	0.0068	HITTERO, NORWAY, 1964
22C	0.4282	0.4801	0.0768	0.0088	0.0045	
23H	0.0012	0.7566	0.0194	0.0045	0.0014	MADRAS, INDIA, 1955 (All analysis by HOWIE)
23C	0.5048	0.8494	0.0530	0.0027	0.0201	
24H	0.0102	0.7354	0.0079	0.0044	0.0022	
24C	0.4977	0.8454	0.0556	0.0043	0.0209	
25H	0.0189	0.6164	0.0088	0.0145	0.0022	
25C	0.4624	0.7516	0.0621	0.0079	0.0067	
26H	0.0152	0.5429	0.0289	0.0056	0.0046	
26C	0.4530	0.6791	0.0709	0.0066	0.0203	
27H	0.0036	0.4289	0.0202	0.0104	0.0017	
27C	0.4398	0.5707	0.0349	0.0074	0.0082	
28H	0.0351	0.3847	0.0254	0.0160	0.0163	
28C	0.4645	0.4930	0.0887	0.0161	0.0251	
29H	0.0192	0.4231	0.0094	0.0219	0.0028	
29C	0.4585	0.5938	0.0205	0.0137	0.0056	
30H	0.0178	0.3687	0.0014	0.0150	0.0043	BROKEN HILL, N.S.W. BINNS, 1962
30C	0.4557	0.5235	0.0027	0.0116	0.0068	

Sample No.	Ca	Mg	Fe+3	Mn	Ti	
31H	0.0253	0.2502	0.0053	0.0297	0.0079	
31C	0.4217	0.3623	0.0332	0.0242	0.0106	
32H	0.0201	0.5251	0.0100	0.0103	0.0044	
32C	0.0201	0.5251	0.0100	0.0103	0.0044	
33H	0.0300	0.3447	0.0090	0.0128	0.0038	BROKEN HILL, N.S.W. -
33C	0.4327	0.4644	0.0172	0.0094	0.0102	BINNS, 1962 (Cont'd.)
34H	0.0185	0.5211	0.0095	0.0051	0.0032	
34C	0.4461	0.6481	0.0168	0.0100	0.0067	
35H	0.0195	0.4946	0.0278	0.0488	N.D.	
35C	0.4534	0.6398	0.0071	0.0079		
36H	0.0184	0.6821	0.0245	0.0029	0.0032	
36C	0.4431	0.7937	0.0619	0.0031	0.0257	DELEGATE, N.S. WALES, AUSTRALIA
37H	0.0080	0.6921	0.1010	0.0090	0.0185	LOVERING & WHITE, 1964
37C	0.5140	0.7979	0.0515	0.0053	0.0070	
38H	0.0265	0.7368	0.0164	0.0072	0.0048	
38C	0.4427	0.8159	0.0123	0.0038	0.0074	LIZARD, CORNWALL - ENGLAND
39H	0.0284	0.6191	0.0151	0.0106	0.0076	D. H. GREEN - 1964
39C	0.4401	0.7354	0.0134	0.0053	0.0159	
40H	0.0392	0.5850	0.0129	0.0130	0.0173	
40C	0.4389	0.6963	0.0182	0.0118	0.0251	

Sample No.	Ca	Mg	Fe^{+3}	Mn	Ti	
41H	0.0298	0.5775	0.0197	0.0112	0.0037	LIZARD, CORNWALL - ENGLAND
41C	0.3962	0.7142	0.0505	0.0053	0.0112	D. H. GREEN - 1964 (Cont'd.)
Note: These specimens were not used in the final analyses.						
42H	0.0135	0.5850	0.0169	0.0121	0.0025	
42C	0.4629	0.7226	0.0497	0.0108	0.0077	
43H	0.0180	0.5717	0.0209	0.0156	0.0025	PENNSYLVANIA & DELAWARE
43C	0.4605	0.7058	0.0546	0.0142	0.0076	
44H	0.0212	0.6098	0.0203	0.0121	0.0027	Orthopyroxene: Clavan et al 1954
44C	0.4610	0.7453	0.0880	0.0108	0.0079	
45H	0.0155	0.6318	0.0194	0.0094	0.0021	Clinopyroxene: NORTON and CLAVAN, 1959
45C	0.4683	0.7697	0.0546	0.0076	0.0087	
46H	0.0402	0.5604	0.0283	0.0067	0.0039	
46C	0.4569	0.6958	0.0387	0.0061	0.0102	
47H	0.0209	0.7045	0.0233	0.0069	0.0013	
47C	0.4676	0.8170	0.0452	0.0059	0.0077	
48H	0.0424	0.7273	0.0134	0.0066	0.0021	
48C	0.4603	0.8257	0.0385	0.0054	0.0106	
49H	0.0105	0.7125	0.0412	0.0032	0.0029	GLENELG, SCOTLAND - O'HARA, 1960
49C	0.4746	0.8174	0.0684	0.0038	0.0058	

Sample No.	Ca	Mg	Fe^{+3}	Mn	Ti	
50H	0.0185	0.6537	0.0290	0.0048	0.0073	
50C	0.4280	0.7448	0.0358	0.0061	0.0203	LAPLAND - ESKOLA, 1952
51H	0.0384	0.4692	0.0037	0.0237	0.0116	
51C	0.4473	0.6019	0.0574	0.0147	0.0200	
52H	0.0132	0.6063	0.0434	0.0122	0.0031	
52C	0.4704	0.7190	0.0712	0.0099	0.0145	
53H	0.0209	0.5112	0.0358	0.0140	0.0063	
53C	0.4561	0.6483	0.0291	0.0136	0.0121	SALTORA, W. BENGAL, INDIA
54H	0.0242	0.5019	0.0237	0.0156	0.0040	SEN AND REGE, 1966
54C	0.4434	0.6243	0.0273	0.0151	0.0108	
55H	0.0148	0.6240	0.0140	0.0101	0.0030	
55C	0.4538	0.7489	0.0224	0.0077	0.0123	
56H	0.0041	0.8065	0.0293	0.0073	0.0006	
56C	0.4566	0.8760	0.0112	0.0066	0.0028	LUTZOW, HOLM BAY, ANTARTICA
57H	0.0021	0.5217	0.0250	0.0127	0.0029	
57C	0.4472	0.6755	0.0767	0.0102	0.0069	

APPENDIX E

DISTRIBUTION COEFFICIENTS

DISTRIBUTION COEFFICIENTS

Ref. No.	K_D(Mg-Fe)	K_D(Fe^{+3}-Mg,Fe)	K_D(Mn-Mg,Fe)	K_D(Ti-Mg,Fe)	
1	0.5661	1.7665	1.2167	1.0536	
2	0.6463	1.0926	1.1655	0.6556	
3	0.5785	0.5567	1.1756	0.3391	SOMERSET ISLAND – J. F. GIGUERE, 1966
4	0.6096	0.1337	1.0918	1.4848	
5	0.5688	0.4425	1.1961	0.1729	
6	0.5758	0.5380	1.2181	0.2839	
7	0.6653	1.5032	1.0956	2.4230	
Average =	0.6019	Average =	1.656		
8	0.4441	0.5474	1.1445	0.0	
9	0.6523	0.7030	1.2043	0.0	
10	0.5461	0.7088	1.1711	0.0	
11	0.6169	0.9515	1.3608	0.0	QUEBEC - KRANCK, 1951
12	0.8432	0.1953	0.6983	0.0	
13	0.5476	0.4984	1.1702	0.0	
14	0.6074	0.3895	1.1713	0.0	
15	0.5758	0.4819	1.2780	0.0	
Av. =	0.6042	Av. =	1.0061		

DISTRIBUTION COEFFICIENTS

Ref. No.	$K_{D(Mg-Fe)}$	$K_{D(Fe^{+3}-Mg,Fe)}$	$K_{DMn-Mg,Fe)}$	$K_{D(Ti-Mg,Fe)}$	
16	1.0219	0.3239	0.3370	0.1433	
17	0.7919	0.7723	0.7912	0.0547	SCOURIE SUTHERLAND - O'HARA, 1961
18	0.6021	0.5191	1.3386	0.1276	
	Av. = 0.8054		Av. = 0.8223		
19	0.5639	0.5989	1.2705	0.1180	SCOURIE SUTHERLAND
20	0.5808	1.4083	1.2477	0.9171	OSLO, NORWAY - MUIR & TILLEY, 1958
21	0.4320	0.3865	1.1293	0.1368	RODIS, SOUTH HARRIS, SCOTLAND, 1964
22	0.6174	0.2518	1.4451	1.5099	
23	0.5510	0.3535	1.6588	0.0697	HITTERO, NORWAY, 1964
24	0.5082	0.1347	1.0121	0.1015	
25	0.5312	0.1338	1.8542	0.3330	MADRAS, INDIA, 1955 (All analysis by HOWIE)
26	0.5613	0.3902	0.8390	0.2247	
27	0.5650	0.5706	1.4134	0.2108	
28	0.6432	0.2675	0.9950	0.6440	
	Av. = 0.6156		Av. = 1.4781		

DISTRIBUTION COEFFICIENTS

Ref. No.	$K_{D(Mg-Fe)}$	$K_{D(Fe^{+3}-Mg,Fe)}$	$K_{DMn-Mg,Fe)}$	$K_{D(Ti-Mg,Fe)}$	
21	0.4320	0.3865	1.1293	0.1368	RODIS, SOUTH HARRIS, SCOTLAND, 1964
22	0.6174	0.2518	1.4451	1.5099	
23	0.5510	0.3535	1.6588	0.0697	HITTERO, NORWAY, 1964
24	0.5082	0.1347	1.0121	0.1015	
25	0.5312	0.1338	1.8542	0.3330	MADRAS, INDIA, 1955 (All analysis by HOWIE)
26	0.5613	0.3902	0.8390	0.2247	
27	0.5550	0.5706	1.4134	0.2108	
28	0.6432	0.2675	0.9950	0.6440	
	Av. = 0.6156		Av. = 1.4781		
29	0.5016	0.4527	1.6205	0.5093	BROKEN HILL, N.S.W. BINNS, 1962
30	0.5317	0.5112	1.3004	0.6361	
31	0.5873	0.1543	1.2344	0.7407	
32	0.5531	0.6960	1.3405	0.4249	
33	0.6067	0.5220	1.3600	0.3720	
34	0.5909	0.5626	0.5114	0.4726	
35	0.5509	4.0168	6.4087	N.D.	
	Av. = 0.5635		Av. = 1.9880		

DISTRIBUTION COEFFICIENTS

Ref. No.	$K_{D(Mg-Fe)}$	$K_{D(Fe^{+3}-Mg,Fe)}$	$K_{D(Mn-Mg,Fe)}$	$K_{D(Ti-Mg,Fe)}$	
36	0.5577	0.3804	0.9450	0.1222	DELEGATE - N.S. WALES, AUSTRALIA
37	0.5692	2.0713	1.7146	2.6753	LOVERING & WHITE, 1964
	Av. = 0.5635		Av. = 1.3298		
38	0.6317	1.3413	1.9115	0.6427	
39	0.5847	1.1314	2.0187	0.4744	LIZARD, CORNWALL - ENGLAND
40	0.6149	0.7059	1.1045	0.6832	D. H. GREEN, 1964
41	0.5471	0.3776	2.1365	0.3244	
Note:	These specimens were not used in the final analyses.				
42	0.5412	0.3283	1.1210	0.3176	PENNSYLVANIA & DELAWARE
43	0.5565	0.3694	1.0995	0.3279	Orthopyroxene: CLAVAN et al 1954
44	0.5338	0.2143	1.1223	0.3360	
45	0.5134	0.3421	0.1319	0.2340	Clinopyroxene: NORTON and CLAVAN, 1959
46	0.5573	0.7226	1.0936	0.3797	
47	0.5340	0.5035	1.1600	0.1647	
48	0.5631	0.3393	1.2203	0.2009	
	Av. = 0.5425		Av. = 0.9927		

DISTRIBUTION COEFFICIENTS

Ref. No.	$K_{D(Mg-Fe)}$	$K_{D(Fe^{+3}-Mg,Fe)}$	$K_{DMn-Mg,Fe)}$	$K_{D(Ti-Mg,Fe)}$	
49	0.5534	0.5859	0.8516	0.4930	GLENELG, SCOTLAND - O'HARA, 1960
50	0.6470	0.8038	0.7937	0.3520	LAPLAND - ESKOLA, 1952
51	0.5846	0.0607	1.6312	0.5744	
	Av. = 0.6158		Av. = 1.2125		
52	0.6017	0.5918	1.2434	0.2130	SALTORA, W. BENGAL, INDIA SEN AND REGE, 1966
53	0.5674	1.2382	1.0304	0.5152	
54	0.6064	0.8644	1.0309	0.3661	
55	0.5564	0.6199	1.3136	0.2433	
	Av. = 0.5830		Av. = 1.2543		
56	0.5898	2.6625	1.1032	0.1963	LUTZOW - HOLM BAY,
57	0.5242	0.3087	1.2545	0.4140	BANNO et al 1964
	Av. = 0.5570		Av. = 1.1489		

PALEOZOIC

? CAMBRIAN

8	Dolomite, sandy dolomite, introformational conglomerate

PROTEROZOIC

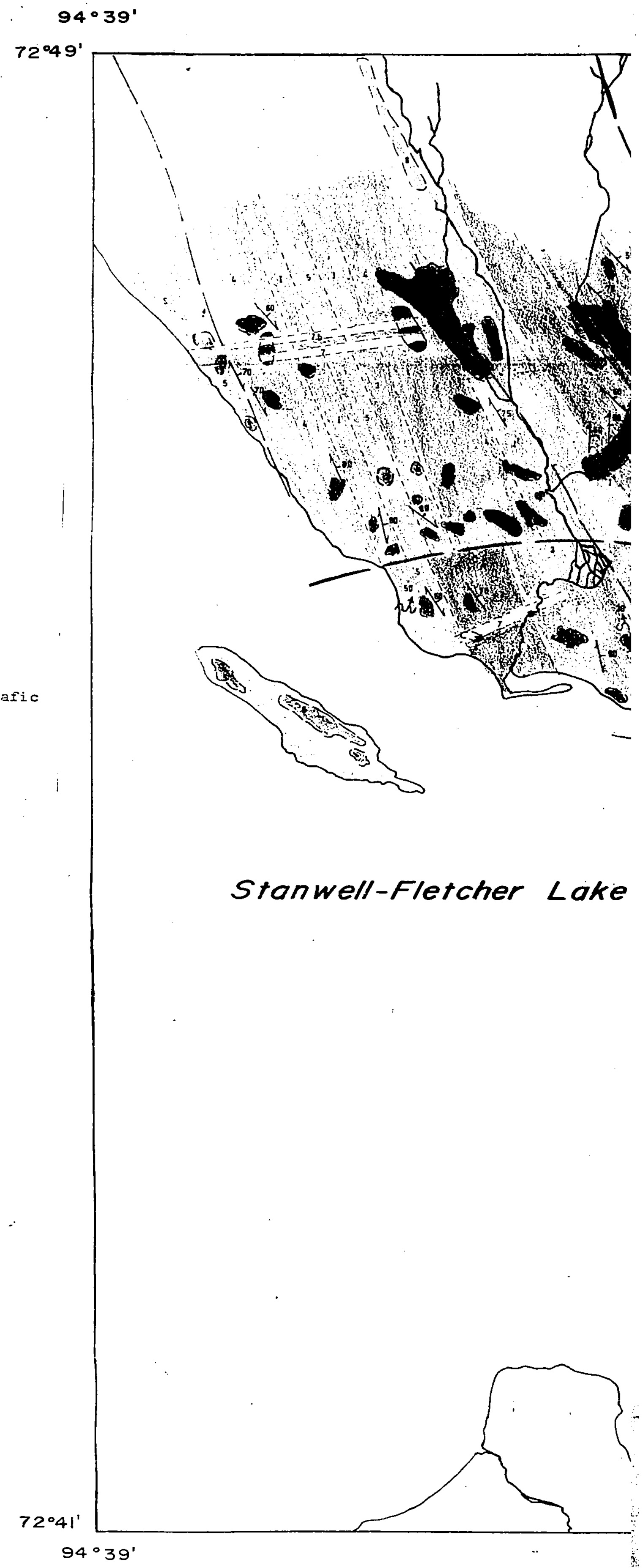
7	Diabase; a) diorite; b)pigeonite gabbro

METAMORPHIC ROCKS

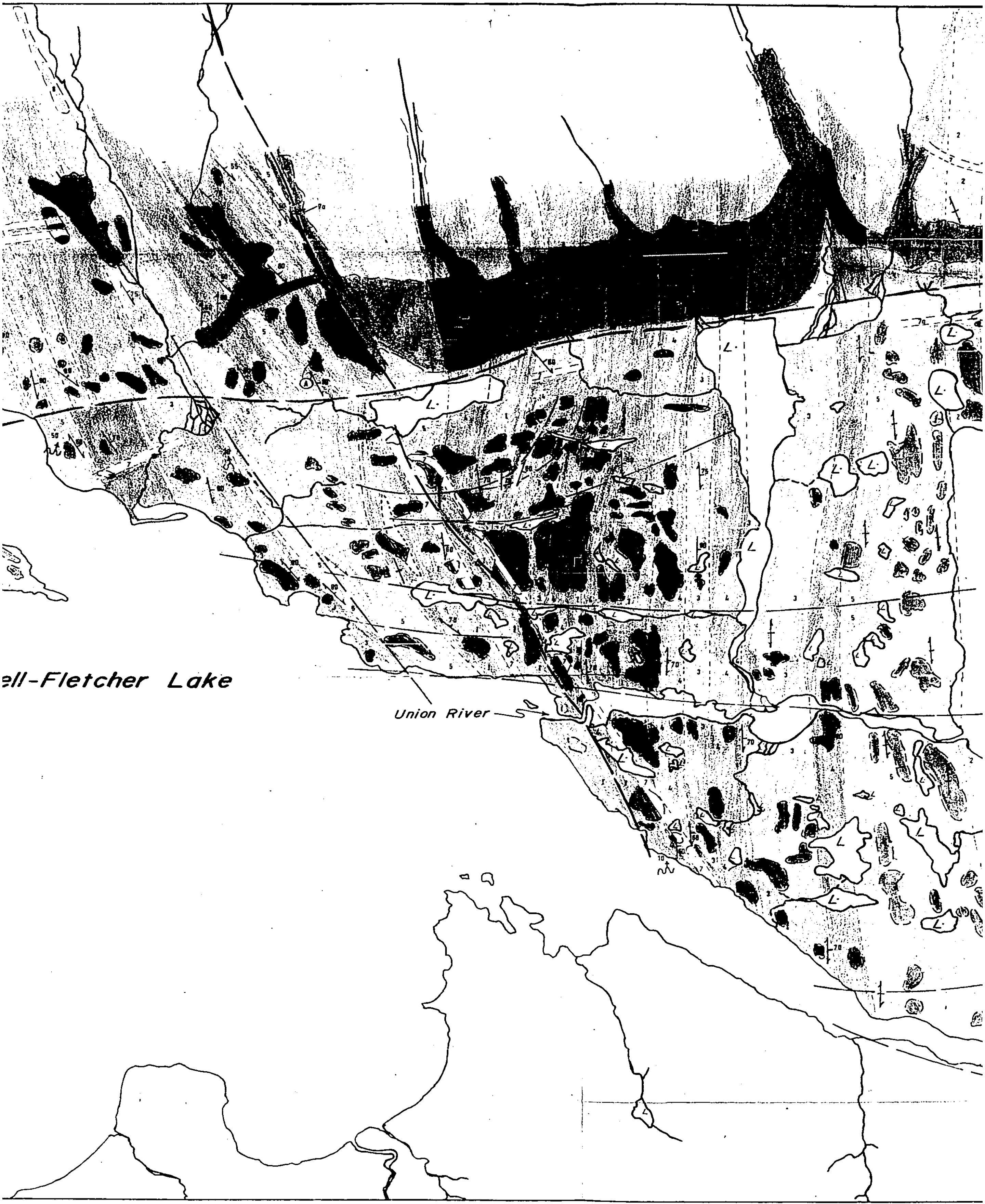
6	Pegmatite
5	Banded quartz-feldspar gneiss
▨	Migmatites
3	Gneisses; High content of mafic minerals
2	Mafic gneisses; Intermediate content of mafic minerals
1	Layered, gneissic quartz diorite

SYMBOLS

	Fault
	Geological boundary; (assumed, observed)
	Lineament
	Area of bedrock outcrop
60	Foliation; (vertical, inclined)
35	Antiform with plunge
Ⓐ	Sapphirine locality
30 20	Drag fold, crenulations; (with plunge)
30	Bedding; (vertical, inclined)
L	Lake

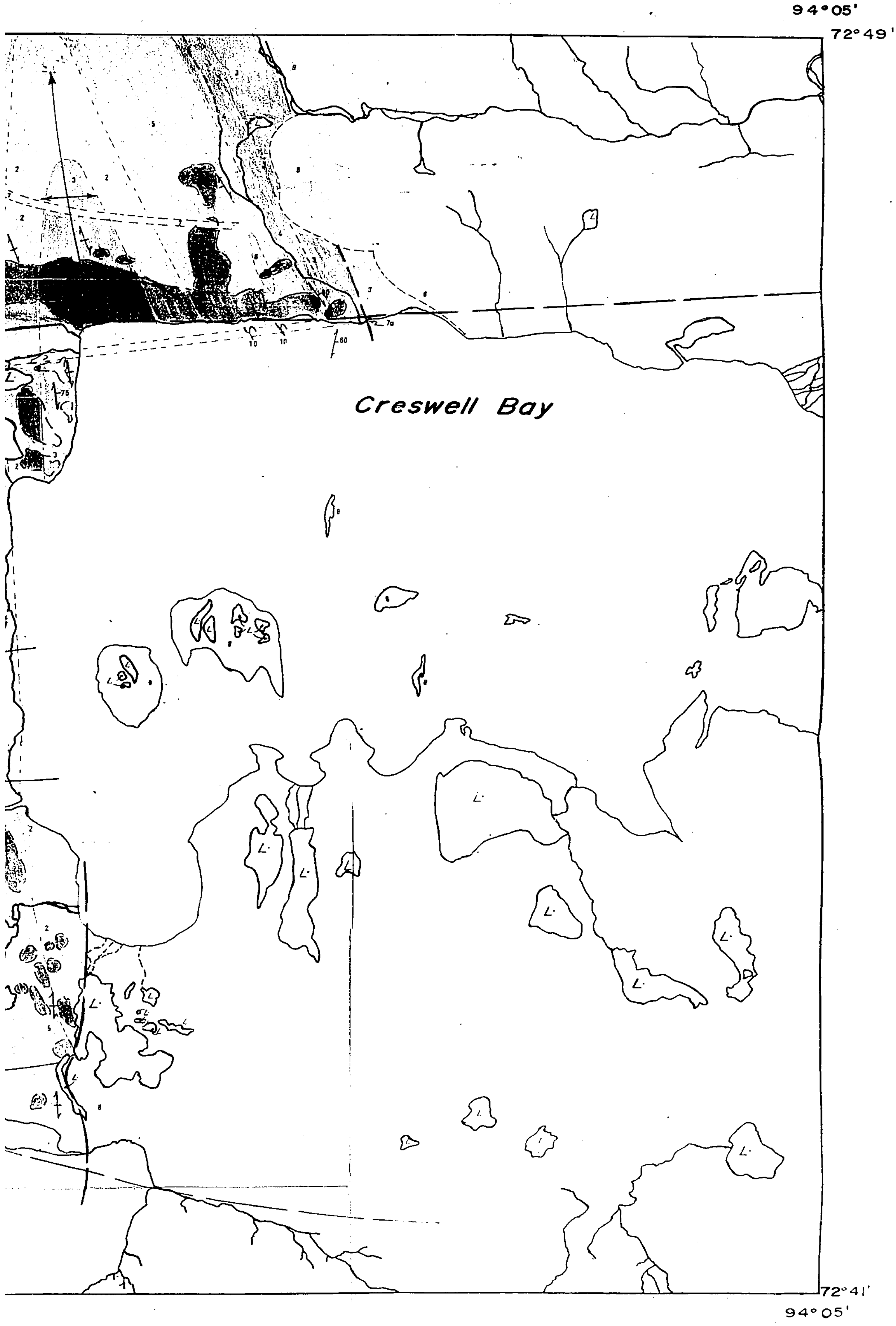


Bedrock geology by: J. F. Giguere (1965)



UNION RIVER, SOMER

N.W.T.



RSET ISLAND.

PALEOZOIC

?CAMBRIAN

8 Dolomite, sandy dolomite, intraformational conglomerate

PROTEROZOIC

7 Diabase; a) diorite; b) pigeonite gabbro

METAMORPHIC ROCKS

6 Pegmatite

5 Banded quartz-feldspar gneiss

3 Migmatites

3 Gneisses; High content of mafic minerals

2 Mafic gneisses: Intermediate content of mafic minerals

1 Layered, gneissic quartz diorite

SYMBOLS

Fault

Geological boundary; (assumed, observed)

Lineament

Area of bedrock outcrop

60 Foliation; (vertical, inclined)

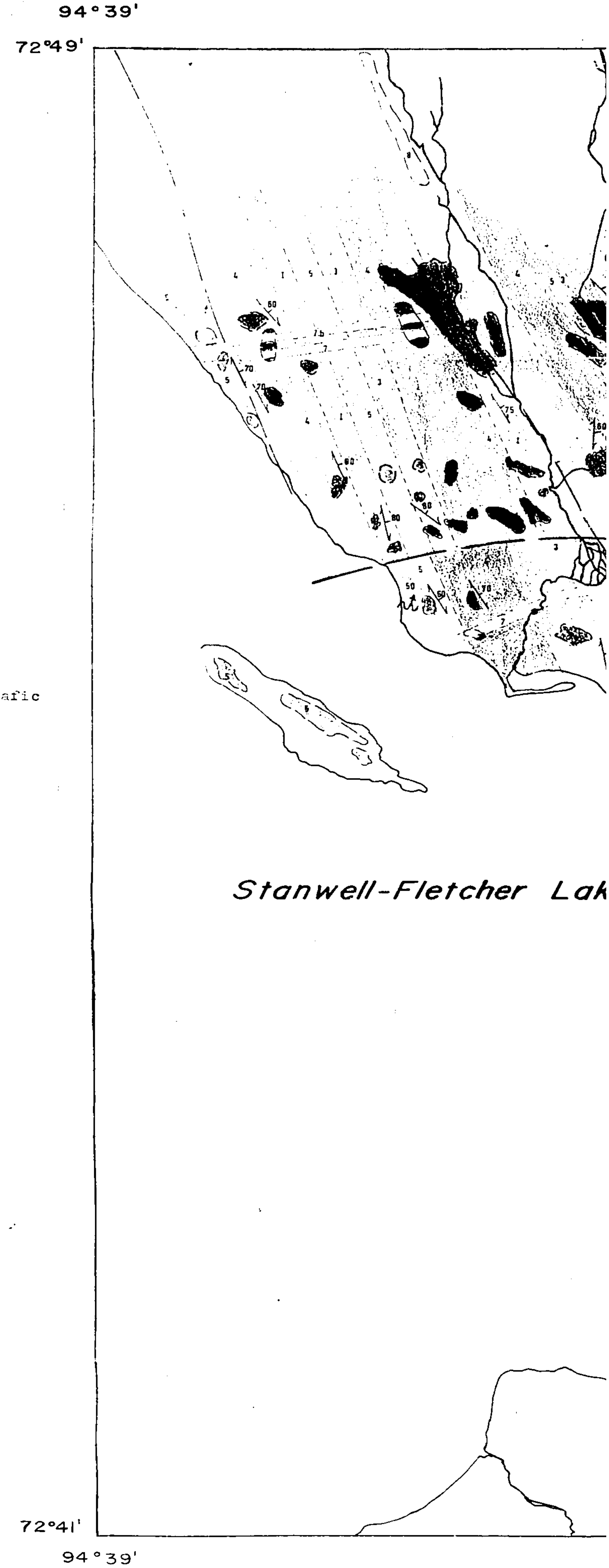
35 Antiform with plunge

Ⓐ Sapphirine locality

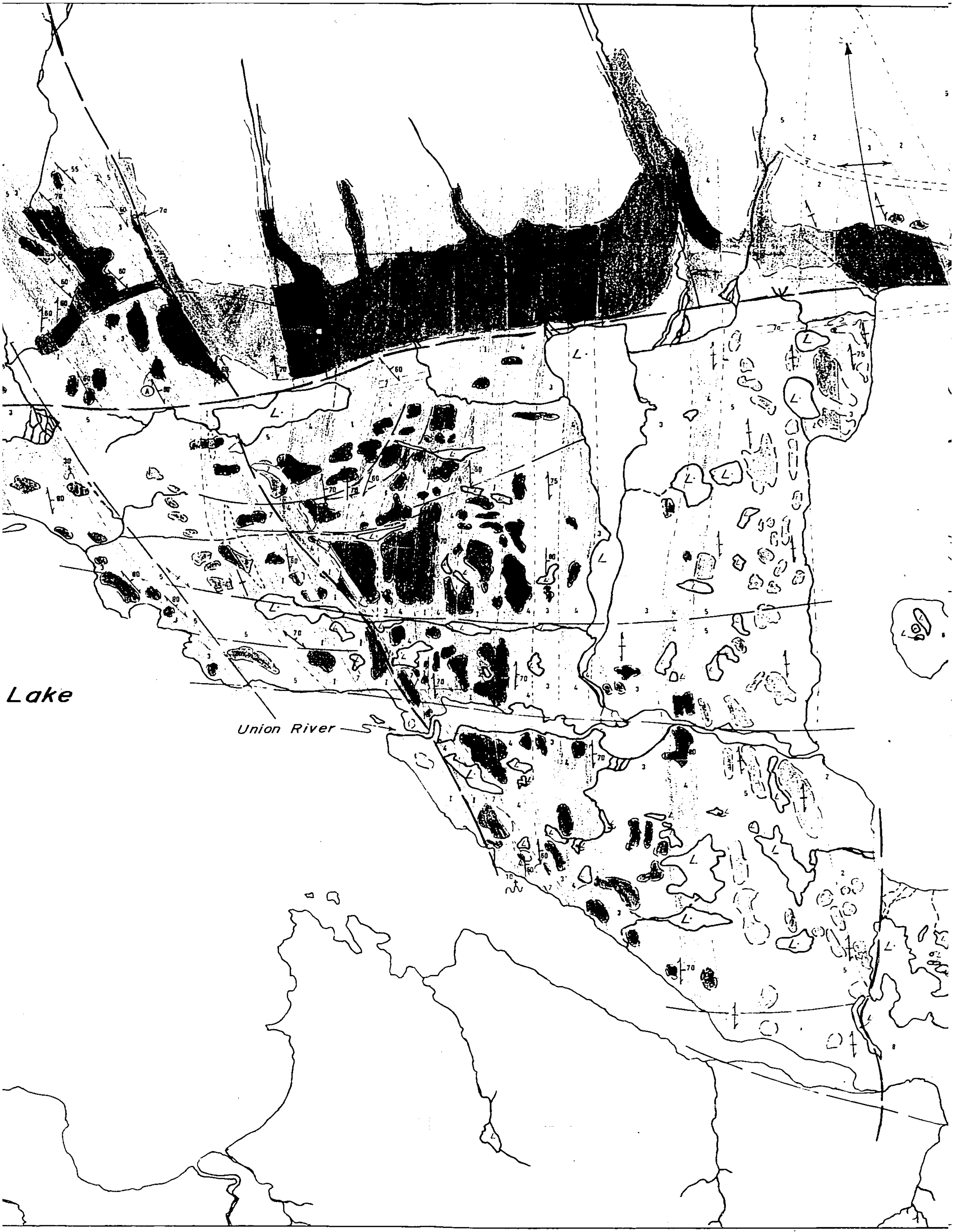
30 30 Drag fold, crenulations; (with plunge)

30 Bedding; (vertical, inclined)

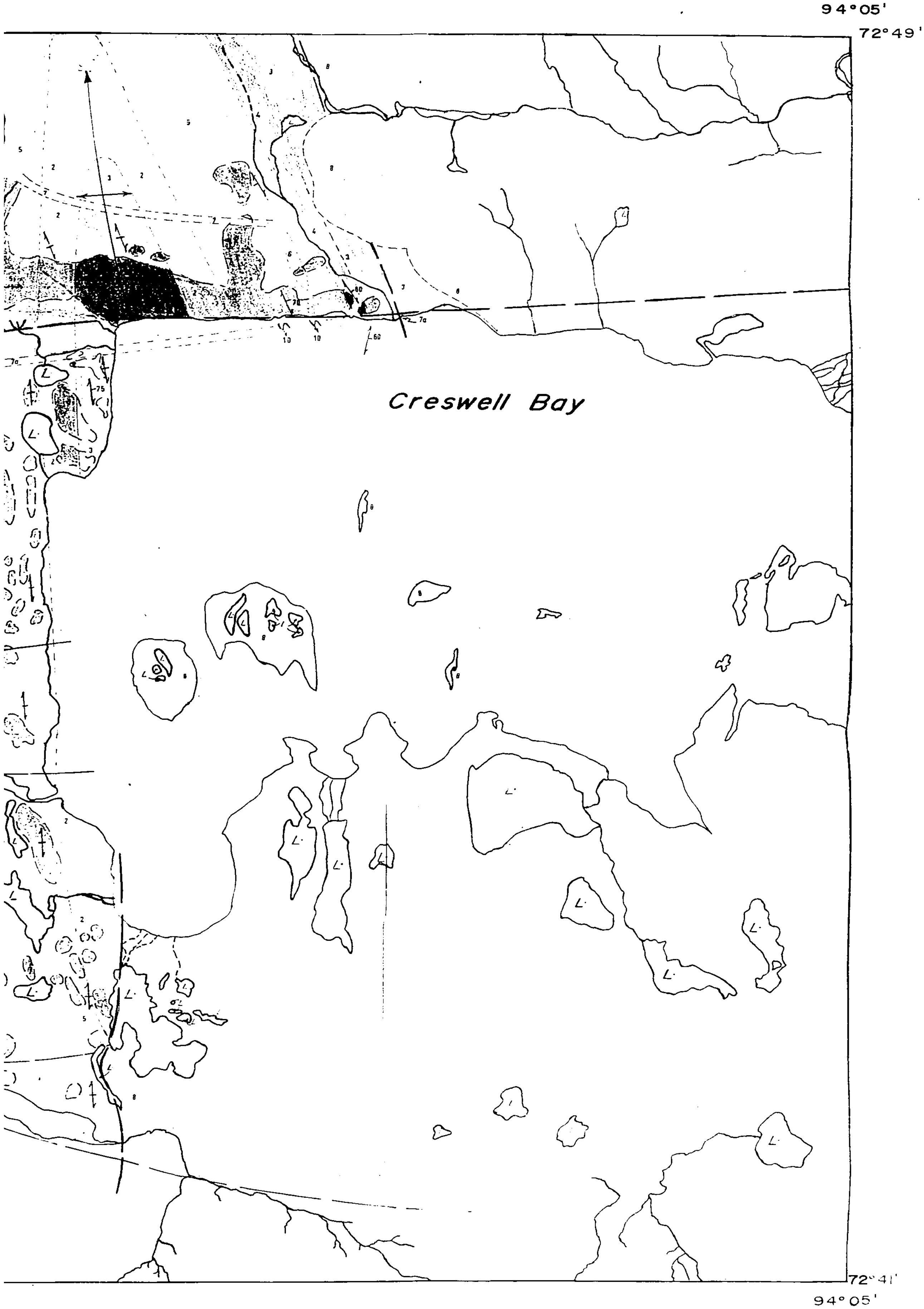
L Lake



Bedrock geology by: J. F. Giguere (1965)



UNION RIVER, SOMERSET N·W·T·



ERSET ISLAND,