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METAMORPHIC PETROLOGY
OF THE AREA BETWEEN
MATTAWA, NORTH BAY AND TEMISCAMING, ONTARIO

BY
RICHARD LEWIS MOORE, B.Sc.

A thesis submitted to the Faculty of
Graduate Studies in partial fulfilment of
the requirements for the degree of Doctor of Philosophy.

Department of Geology
Carleton University
Ottawa, Ontario

July 1976

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The undersigned hereby recommend to the
Faculty of Graduate Studies acceptance of this thesis,
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ABSTRACT

Geological mapping has been carried out between latitudes $46^{\circ}15'$ and $46^{\circ}45'$ and longitudes $78^{\circ}45'$ and $79^{\circ}15'$ in the Mattawa - North Bay - Temiscaming area, Ontario. Detailed mapping ($\frac{1}{4}$ mile to the inch) was done in the vicinity of Timber Lake ($46^{\circ}30'; 79^{\circ}02'$) Cahill Lake ($46^{\circ}22'; 79^{\circ}03'$) and Miner's Lake ($46^{\circ}41'; 79^{\circ}07'$).

From detailed mapping, three informal units, the Butler Gneiss, the Antoine Gneiss, and the Jocko Gneiss have been distinguished. The Butler Gneiss is composed of siliceous meta-sediments, mainly of psammitic composition but containing layers of marble, pyrrhotite gneiss, pelitic gneiss, calcsilicate gneiss, and amphibolite. The Antoine Gneiss is a migmatitic biotite - oligoclase gneiss which has been interpreted as meta-greywacke. The Jocko Gneiss is a meta-granite.

Four phases of folding have been recognized in the Mattawa area. F_1 is recumbent and isoclinal with variable axial trends. F_2 is tight and upright with an axial trace parallel to F_1 . F_3 is upright and tight with both northwest and northeast axial traces. F_4 is open with an upright northeast trending axial plane.

The major mineral assemblages in the calcsilicate rocks are:

- 1) biotite - calcite - quartz - hornblende - plagioclase - epidote
- 2) biotite - calcite - quartz - potassic feldspar - hornblende -
epidote - plagioclase
- 3) biotite - quartz - potassic feldspar - hornblende - plagioclase -
epidote

No systematic distribution of these assemblages exists and isograds in the calcsilicate assemblages could not therefore be mapped in the Mattawa area.

The mineral assemblages in the psammitic rocks exhibit a muscovite-out isograd, but this isograd was not precisely located in the field.

The pelitic rocks have the assemblage muscovite - quartz - biotite - garnet - kyanite.

A petrogenetic grid for the calcsilicates was constructed for pressures from 2000 to 10,000 bars based on the following equilibria most of which have passed stringent thermodynamic tests for internal consistency.

$$\log K_1 = \frac{-31,362.}{T} + 64.92 + \frac{0.8004 (P - 2000)}{T}$$

$$\log K_2 = \frac{-12,486.}{T} + 27.95 + \frac{0.5152 (P - 2000)}{T}$$

$$\log K_3 = \frac{-4,463.}{T} + 8.130 + \frac{0.0164 (P - 2000)}{T}$$

$$\log K_4 = \frac{-10,029.}{T} + 19.09 + \frac{0.0705 (P - 2000)}{T}$$

$$\log K_5 = \frac{-8,988.}{T} + 18.74 + \frac{-0.2754 (P - 2000)}{T}$$

$$\log K_6 = \frac{-49,909.}{T} + 93.97 + \frac{1.1123 (P - 2000)}{T}$$

The equilibrium model defined by the above equations and augmented by additional experimental data

$$\log K_{26} = \frac{-320}{T} + 2.6 + \frac{-0.3463 (P - 1)}{T}$$

has been used with a Temkin solution model to estimate the following minimum conditions for the Mattawa area: Pressure, 8.4 kilobars; Temperature, 725°C; x_{CO_2} , 0.32.

ACKNOWLEDGEMENTS

I would like to extend my appreciation to Dr. G.B. Skippen for his advice, and support during the preparation of this thesis.

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NOTATION AND DEFINITIONS

X mole fraction

T temperature in degrees Kelvin

t temperature in degrees centigrade

a activity

f fugacity

R gas constant

K equilibrium constant

P pressure in bars

C_p heat capacity

$\Delta H_r^0(298,1)$ standard enthalpy of reaction at 298° Kelvin and
1 bar

ΔS_r^0 standard entropy change of reaction

ΔV_r^0 standard change in volume of the solids during a reaction

$\Delta G_r^0(298,1)$ standard Gibbs free energy of reaction at 298°
Kelvin and 1 bar

S_f^0 standard entropy of formation from the elements at 298°
Kelvin and 1 bar

Standard states for Gibbs free energy are defined as:

CO₂ and H₂O: the ideal gas at 1 bar of pressure and temperature
of interest.

solids: the pure mineral at 2000 bars pressure and temperature
of interest.

Fugacity coefficients: Burnham and Wall (personal communication
to G.B. Skippen) for CO₂, H₂O from Burnham, C.W., Holloway, J.R. and
Davis, N.F., 1969, Geol. Soc. Amer., Special Paper 132.

ABBREVIATIONS

Ab	Albite	Ea	Eastonite	Opx	Orthopyroxene
Ad	Andalusite	En	Enstatite	Or	Orthoclase
Af	Arfvedsonite	Ep	Epidote	Ox	Oxide
Al	Almandine	Gt	Garnet	Pf	Plagioclase
Am	Amphibole	Gf	Graphite	Ph	Phlogopite
An	Anorthite	Gs	Grossular	Po	Pyrrhotite
Ap	Apatite	Gu	Grunerite	Pt	Perthite
As	Arsenopyrite	Hb	Hornblende	Py	Pyrite
At	Anthophyllite	He	Haematite	Qz	Quartz
Bi	Biotite	Hy	Hypersthene	Rt	Rutile
Bo	Bornite	Id	Iddingsite	Sc	Scapolite
Ca	Chalcocite	Il	Ilmenite	Sl	Sillimanite
Cb	Carbonate	Kf	Potassium Feldspar	Sn	Spinel
Cc	Calcite	Ky	Kyanite	Sp	Sphene
Ch	Chlorite	Ma	Malachite	Sr	Serpentine
Cm	Cummingtonite	Mc	Marcasite	Su	Sulphide
Cp	Chalcopyrite	Mt	Magnetite	Tc	Talc
Cz	Clinozosite	Mv	Muscovite	Tm	Tourmaline
Di	Diopside	Ol	Olivine	Tr	Tremolite
Do	Dolomite	Op	Opaque	Zr	Zircon

ABBREVIATIONS

alt	Altered
Bi-Di	Minerals are not part of same assemblage
Fe	Iron rich
Mg	Magnesium rich
rr	Retrograde
t	Trace
23	An ₂₃
z	Zoned

INTRODUCTION

The field area to be described in this thesis was first visited by the writer in the late summer of 1970, during an examination of a small group of claims on Crocan Lake, near Mattawa, Ontario, for Canex Aerial Exploration Co. Ltd. While examining this property, a variety of interesting rock types was observed in contrast to the generally held view that the rocks of this area were a homogenous, gneissic sequence which did not warrant petrologic study. The rock types which were observed while visiting the claims near Crocan Lake, indicated that there were many problems to be solved in this area, and for this reason, the area was chosen as a thesis topic.

As no geologic maps of the area were available at the time of the initiation of the thesis, the area first had to be mapped to obtain an understanding of the distribution of rock types, the stratigraphy and the structure of the area. The results of this study are presented in Chapter I.

The metamorphic petrology of the area was studied in an attempt to find isograds and thereby deduce the metamorphic conditions which formed the mineral assemblages.

The calcsilicate rocks were chosen for detailed examination because they were widespread throughout the area and appeared to show the greatest variability in mineral assemblages. It was somewhat surprising, however, to discover that mineral isograds could not be identified in the calcsilicates from Mattawa to as far north as the Grenville Front. This aspect of the study is reported in Chapter II of the thesis.

The field studies were carried out in conjunction with a theoretical study of the metamorphic petrology of calcsilicates.

An equilibrium model for the metamorphism of calcsilicates is described in Chapter III and is based on equilibrium constants for calcsilicate reactions that have been studied in the laboratory. The experimental results that have been used were subjected to a series of tests to establish the thermodynamic consistency of the experimental data. The resulting model is displayed in a variety of ways in Chapter III including a table of equilibrium constants for 74 reactions that apply to calcsilicates, a series of isothermal, isobaric activity diagrams that display the effect of fluid composition on the stability of mineral assemblages as well as isobaric temperature - mole fraction CO_2 diagrams that illustrate simultaneously the effect of temperature and fluid composition on mineral stabilities.

Chapter IV describes the application of the equilibrium model to rocks from the Mattawa area as well as to similar rocks from other areas. The discussion in Chapter IV illustrates the manner in which models for metamorphism can be applied to field areas without reference to the classical approach of mapping isograds. The limited amount of chemical data that have been measured for rocks from the Mattawa area make it impossible to offer definitive results for the metamorphic conditions that produced the observed mineral assemblages. However, the approach is sufficiently well documented that the collection of additional chemical data is all that will be required to produce an accurate statement about the metamorphic history of the Mattawa area.

CHAPTER I GEOLOGY OF THE MATTAWA AREA

I-1 INTRODUCTION

The Ontario Gneiss Segment of the Grenville Province was first suggested as a subdivision of the Grenville Province by Wynne-Edwards (1972). This subdivision together with the Quebec Gneiss Segment (see figure I-1) form a central core of gneissic rocks within the western half of the Grenville Province. This central core of gneisses is described by Wynne-Edwards as starting where the north-east trending foliation and cataclasis of the Grenville Front Tectonic Zone become inconspicuous. To the south of the central core of gneisses the pattern of aeromagnetic anomalies changes from one of weak, linear trends within the gneisses to one of strong and irregular trends within the Central Metasedimentary Belt and the Central Granulite Terrain.

In the Ontario Gneiss Segment, the dominant foliations and structures are northwesterly, whereas in the Quebec Gneiss Segment, they are more irregular. The Ontario Gneiss Segment is underlain principally by quartzo-feldspathic gneisses with minor amounts of quartzite, pelitic gneisses, marbles, and iron formation (Lumbers 1971, 1971b, 1971c, 1975, and Rive 1969, 1972, 1973a, 1973b). South of Sudbury, Quirke and Collins (1930), Pearson (1962), Dalziel, Brown and Warren (1969) and others found rocks to the southeast of the Grenville Front which could be correlated with less altered rocks to the northwest of the Front. Lumbers, working on the Burwash, Tomiko, and North

Figure I-1 Tectonic Framework of the Grenville Province from Wynne-Edwards (1972).

Bay sheets, also suggested that the gneisses were metamorphosed equivalents of Huronian Supergroup rocks. Moreover, to the south of Temagami Lake, Grant (1964), and Lumbers (1971a) have reported the presence of Archean rocks within the Grenville Structural Province.

Radiometric dating along the northern edge of the Grenville Province suggests that the major metamorphic or thermal event occurred at around 1.8 ± 0.1 bys. (Krogh et al 1968, Davis et al 1970, Krogh and Davis 1969a, 1969b). This age corresponds with the Penokean Orogeny which is recognized in rocks from the Southern Province. Brocoum and Dalziel (1974) have traced Penokean structures from the Southern Province near Sudbury across the Grenville Front and have not seen evidence of any later event superimposed on the Penokean structures. Only further south away from the front is evidence of the Grenville Orogeny found, and then only as a thermal event (Krogh and Davis 1969).

A Rb-Sr whole rock isochron from a migmatitic rock from the Mattawa area has given an age of approximately 1.1 bys. (Bäer, personal communication). This is a Grenville age; therefore the Mattawa area must have undergone metamorphism at about 1.1 bys. which was capable, at least, of resetting the Rb-Sr date. How close to the Grenville Front the effect of the Grenville Orogeny can be traced to the north of the study area is unknown at present.

I-2 LOGISTICS

The area of study is enclosed by the towns of Mattawa, North Bay and Temiskaming (Figure I-2). It is predominantly a heavily wooded plateau which has been cut by the Ottawa, Mattawa and Jocko Rivers.

Figure I-2 Location Map.

Access is by highways 533, 63, 17, old lumber roads and the Ottawa River. Transportation was by truck, motorcycle, canoe and foot. Certain parts of the area were inaccessible using the above methods and so were not visited.

Geological data were collected by traversing through the bush using pace and compass methods, with aerial photographs for geographic control. Field work was carried out during the summers of 1971, 1972, and 1973. Geological assistants for those summers were David Hendrick, Barbara Moore, and Doug Dubord, respectively.

I-3 PREVIOUS WORK

The first geological references to the area are by J.J. Bigsby in 1883 who traversed from Mattawa to the north shore of Lake Huron. His most important observation was the presence of marble at Rutherglen.

William Logan did the first geological mapping in 1846. He mapped the Ottawa River to the head of Lake Temiscaming and along the Mattawa River to Trout Lake. Logan describes the rocks from Pembroke to the Montreal River as follows, "The lowest rocks which this undulation brings to the surface are of a highly crystalline quality belonging to the order which in the nomenclature of Lyell, is called metamorphic instead of primary, as possessing an aspect inducing a theoretical belief that they may be ancient sedimentary formations in an altered condition."

In 1899, A.E. Barlow published his "Geology and Natural Resources of the area included by the Nipissing and Temiscaming Map Sheets". Despite finding kyanite in some of the gneisses near Snake

Creek, he considered the whole area of gneisses to be foliated intrusive.

W.D. Harding was the next geologist in the area, and in 1943 he mapped Mattawan and Olrig Townships in search of muscovite pegmatites. He divided the area into two units: pink gneiss, and dark gneiss.

More recently Lumbers has published regional maps of the area, the Tomiko sheet in 1971, and the North Bay sheet also in 1971. He says, "For the most part, the North Bay area is underlain by a metamorphic complex of gneissic rocks regionally metamorphosed to the almandine amphibolite facies, although intrusive and sedimentary rocks younger than the metamorphic complex are also present;.....
.....The oldest and most abundant rocks of the metamorphic complex are metasediments derived largely from siliceous sandstone and siltstone that probably accumulated to considerable thickness during Middle Precambrian time, but whose base is unknown. Calcsilicate gneiss and rare impure marble, the products of both clastic and chemical sedimentation, are interlayered locally with the clastic siliceous metasediments."

Lumbers also states that the metasediments could be a eugeo-synclinal facies of the Huronian Supergroup.

Maurice Rive has worked on the Quebec portion of the Ontario Gneiss belt and published maps in 1969, 1972, and 1973. The results obtained by Rive are compatible with the interpretation suggested by Lumbers (1971a).

I-4 GEOLOGICAL MAPS

Five geological maps (in pocket) have been drawn to show the detailed and regional geology of the area. The location of these maps is shown on figure I-3. They are:

Map 1: Scale 1" to 1/8 mile - Detailed geology around the Crocan Lake Area.

Map 2: Scale 1" to 1/4 mile - Geology around the Timber Lake Area.

Map 3: Scale 1" to 1/4 mile - Geology around the Cahill Lake Area.

Map 4: Scale 1" to 1/4 mile - Geology around the Miner's Lake Area.

Map 5: Scale 1 to 50,000 - Regional Geology enclosing the area between Mattawa, North Bay and Temiscaming.

The rocks of the area have been divided into six main units as shown on Table I-1. They are in order of structural sequence:

1) the Butler Gneiss, 2) the Antoine Gneiss, which is a biotite-oligoclase gneiss, 3) the Jocko Gneiss, a foliated granite, 4) monzonitic intrusive rocks, 5) mafic and ultramafic plutonic rocks, 6) unmetamorphosed quartz monzonite. Also, unmetamorphosed diabase dykes were observed at a number of locations.

The Butler Gneiss has been further subdivided into six lithologic units as follows: 1a) Marble, 1b) Pyrrhotite Gneiss, 1c) Pelitic Gneiss, 1d) Calcsilicate Gneiss, 1e) Psammitic Gneiss, and 1f) Amphibolite.

Figure I-3
LOCATION OF
MAPPED AREAS

Table I-1
TABLE OF FORMATIONS

	Diabase dykes		
6	Quartz Monzonite		
5a	Mafic	Intrusive Rocks	
5b	Ultramafic		
4	Monzonitic Intrusive Rocks		
3	Granite Gneiss	}	JOCKO GNEISS
2	Biotite-plagioclase Gneiss	}	ANTOINE GNEISS
1f	Para-amphibolite	}	BUTLER GNEISS
1e	Psammitic Gneiss		
1d	Calcsilicate Gneiss		
1c	Pelitic Gneiss		
1b	Pyrrhotite Gneiss		
1a	Marble		

Map 1 was made at the scale of one-eighth of a mile to the inch to get good sampling detail in the Calcsilicate Gneiss unit of the Butler Gneiss, and to establish better contact relations around Crocan Lake. Excellent control was obtained around Crocan Lake and along the strike of the Pelitic Gneiss. Control is very poor south of Tremblay Lake as the area is almost completely covered by glacial drift. The measured foliation is a mica fabric which is parallel or sub-parallel to bedding, where bedding is recognized. More than one generation of foliation may be included in these measurements.

Outcrops are usually low ridges, but along the west side of the Ottawa River about $1\frac{1}{2}$ miles south of the mouth of the Jocko River, outcrops are much larger. The topographic relief along the river is up to five hundred feet and outcrops here are large ridges and cliffs. In this area there is so much variation of the rock types within the Butler Gneiss that they could not be mapped separately. Psammitic gneiss dominates with interlayered calcsilicate and pelitic rocks.

The Pyrrhotite Gneiss is difficult to find. It weathers very easily and is always found beside the very resistant Pelitic Gneiss. Pyrrhotite Gneiss is usually found on lake shores and in low ground.

Map 2 is made at the scale of $\frac{1}{2}$ mile to the inch and includes the area of map 1. Most areas of easy access were visited, while more remote areas had to be ignored. Two areas, around the road to Coxey's Camp and around Twist and Transparent Lakes are completely covered in glacial drift.

The area between the Dillow Lakes and highway 533 is overgrown with maple saplings and it was therefore extremely difficult to

keep a steady and straight traverse through the area. For this reason, some outcrops in this area may be slightly misplotted. As the structure in this area is complex, the geological contacts are not reliable as shown. The Pyrrhotite Gneiss here is shown only as a few small occurrences, but could easily be a narrow continuous band, outcropping in only a few places.

The interpretation of the outcrop pattern around the nose of the fold defined by unit 1e southwest of Tremblay Lake is a major problem. Exposure is poor and access is difficult so little control is available. Alternative interpretations could be drawn from the existing data and more work in this area will be necessary.

Map 3 is south of maps 1 and 2 and is from the Cahill Lake area, the scale being $\frac{1}{4}$ mile to the inch. The area was selected in order to study the Muscovite-out "isograd" and also to study phase relations in rocks containing the assemblage kyanite-hornblende. The work was done in this area by mapping along the Ontario Hydro transmission line from La Cave to North Bay, and traversing through the bush at right angles to the power line. Outcrop is quite plentiful in the area mapped, except north of Cahill Lake. To the northwest of Cahill Lake, the traverses proved to be parallel to strike so good geological control on the contacts was not obtained.

Map 4 is from the area around Miner's Lake which is two miles southwest of Temiscaming. The purpose of mapping this area was to obtain more samples of the Pyrrhotite Gneiss to compare samples from the Miner's Lake area with rocks of the same unit from the Crocan Lake area. The geology was done mainly on a lumber road which goes part way into Miner's Lake. One traverse on foot was done from

Plate 1 Marble outcrop not far from Miner's Lake. Marble outcrops are found only where lumbering operations have stripped the topsoil. From station B-350-73 on Map 4.

Plate 2 The pyrrhotite gneiss is found as weathered low lying outcrop. From station B-350-73 on Map 4.

the lumber road into Miner's Lake. This foot traverse (stations B-62-72 to B-365-73) showed that in detail, the geology is more complicated than is shown on this map.

Map 5 is a compilation map which includes data from maps 1 to 4, further mapping not included on these maps, and data from Lumbers (1971b, 1971c). Around the town of Mattawa, no geological maps are available.

Other than the areas on maps 1 to 4, work was done along highways 63 and 533, the power line, the Ottawa River, and along all lumber roads and trails in the area. The reliability of the interpretation is indicated on all maps by the continuity of the symbol used to show the contact.

I-5 DESCRIPTION OF ROCK TYPES

I-5.1 Unit 1a. Marble

The Marble is rarely seen and was found in only three localities: near Rutherglen as roof pendants in the Bonfield Batholith, in the centre of the Pyrrhotite Gneiss near Miner's Lake (see plate 1), and associated with magnetite iron-formation near McLaren Point, which is located 12 miles north of Temiscaming on the Ottawa River. The locality near Rutherglen contains brucite and has been described by Harding (1943) and Garrison (1974).

I-5.2 Unit 1b. Pyrrhotite Gneiss

The Pyrrhotite Gneiss is found only in three localities. One is in an east-west belt near Miner's Lake. A second is in the core of

the large fold which is found outcropping on ~~Sparks~~ and Crocan Lakes, and a third is in the fold structure south of Timber Lake and north of the Dillow Lakes.

The Pyrrhotite Gneiss is more accurately described as a quartz-microcline gneiss with minor amounts of pyrrhotite and pyrite. The sulphides, however, weather out leaving the outcrop a rusty brown colour which is very diagnostic (see plates 2 and 3). Small amounts of calcite are also found in this unit, which, along with the sulphides, make it highly susceptible to weathering; as a result, it is not often seen in outcrop. Due to the extreme weathering of this unit, identification of minerals was difficult. Other minerals identified were biotite, tremolite, diopside, plagioclase, chlorite, and possibly muscovite. Accessories were apatite, tourmaline, rutile, sphene, and occasionally chalcopyrite. The mafic silicates are all magnesium-rich.

1-5.3 Unit 1c. Pelitic Gneiss

The Pelitic Gneiss is a muscovite-biotite-quartz-almandine-kyanite gneiss which is bluish in colour. The amount of kyanite normally varies in the rock from 5 per cent to 25 per cent, but on the north shore of Crocan Lake it contains over 90 per cent kyanite. The pelitic gneiss is a coarse-grained rock with a lepidoblastic texture (see plate 4). The garnets are poikiloblastic and in the Timber Lake area are up to 1 cm. in diameter. Around Miner's Lake the garnets are usually less than 5 mm., but they have rotated inclusion trails. Muscovite is strained and bent around minor folds and crenulation in the rock (plate 4). Kyanite often forms porphyroblasts up to 5 cm. in

Plate 3 Pyrrhotite Gneiss from Miner's Lake area. Photograph shows isoclinal fold with quartz in the core. From station B-355-73 on Map 4.

Plate 4 Sample B-351-73. 10X. Crenulated muscovite from pelitic gneiss of Miner's Lake area. 1mm

Table I-2 Whole rock wet chemical analysis of several rock types. Analysis by C. Murray.

	B-71-2	B-71-4	B-71-10	B-71-51	CS	B-71-66	B-71-99	B-71-14	B-71-28	Hb-Ky	B-71-45
SiO ₂	72.28	69.70	78.03	82.09	69.18	61.07	61.88	55.39	52.74	47.50	66.45
TiO ₂	0.39	0.50	0.25	0.63	0.39	0.77	0.56	0.63	0.98	1.06	0.68
Al ₂ O ₃	13.75	15.31	13.75	10.90	10.12	16.95	13.93	16.69	17.65	17.99	16.09
Fe ₂ O ₃	0.19	0.17	0.91	3.17	3.11	3.01	5.36	1.87	1.54	0.95	0.93
MgO	0.09	0.12	0.24	0.23	2.98	2.72	2.38	5.73	6.38	8.13	0.55
FeO	3.39	4.52	0.84	1.54	2.48	2.91	1.45	6.88	7.63	8.97	4.15
MnO	0.09	0.12	0.03	0.03	0.09	0.12	0.12	0.19	0.14	0.14	0.11
CaO	0.72	1.09	0.04	0.17	9.59	3.28	13.19	8.69	8.33	9.64	2.16
Na ₂ O	1.11	4.66	0.45	0.41	0.24	3.55	0.48	2.25	2.47	2.28	3.31
K ₂ O	5.27	4.84	5.51	2.50	0.17	3.02	0.11	1.22	0.46	0.53	5.04
P ₂ O ₅	0.04	0.08	0.03	0.08	0.03	0.22	0.16	0.17	0.10	0.19	0.18
TOTAL	97.32	101.12	100.08	101.75	98.38	97.62	99.62	99.67	98.42	97.38	99.65

Table 1-2 (Continued)

B-71-2	Jocko Gneiss	Greenish meta-granite
B-71-4	Jocko Gneiss	Pink meta-granite
B-71-10	Butler Gneiss	Psammitic Gneiss with 15% muscovite
B-71-14	Butler Gneiss	Calcsillicate mainly hornblende and quartz
B-71-28	Butler Gneiss	Amphibolite Garnet-hornblende-plagioclase gneiss
B-71-45	Antoine Gneiss	Biotite Gneiss with some garnets
B-71-51	Butler Gneiss	Psammitic Gneiss from Cahill Lake area
B-71-66	Butler Gneiss	Calcsillicate Gneiss Epidote rich
B-71-99	Butler Gneiss	Calcsillicate Gneiss Epidote rich
C.S.	Butler Gneiss	Calcsillicate Gneiss Epidote rich
Hb-Ky	Butler Gneiss	Amphibolite Kyanite-hornblende

length, although 1 cm. is more common. The kyanites have been bent and show continuous extinction in fold noses (plate 5).

Accessory minerals are apatite, tourmaline, graphite, Fe-Ti oxides and zircon.

I-5.4 Unit 1d. Calcsilicate Gneiss

The Calcsilicate Gneiss includes rocks that have a varied appearance in hand specimen. All of these rocks, however, have a similar bulk composition and origin. Included in the calcsilicate gneisses are; epidote-muscovite-calcite gneiss (see plate 16), biotite-epidote-hornblende gneiss (see plate 6), and hornblende-plagioclase gneiss (see plate 7). The presence of epidote is an important indication of the calcareous rocks, but epidote is not always present, as in the hornblende-plagioclase gneiss. Moreover, epidote is sometimes found in other rock types. The hornblende-plagioclase gneiss is difficult to distinguish from the restite phase of migmatitic biotite rocks in the Antoine Gneiss.

The mafic content of the Calcsilicate Gneiss is usually around 50 per cent, although in some cases it does go as high as 90 per cent. Several samples of this unit were analysed using wet chemical techniques, and the results are shown on Table I-2. The results are consistent with the conclusion that the Calcsilicate Gneiss is derived from calcareous sedimentary rocks.

Calcareous gneiss is found at more than one horizon in the stratigraphic succession. The major occurrence is a mappable unit (unit 1d) overlying Pelitic Gneiss (unit 1c). Other layers of calcareous gneiss are less than 100 feet thick and are found within the

Plate 5 Sample B-320-72. 10X. Note Bent kyanite crystals in pelitic gneiss.

1mm

Plate 6 Typical occurrence of layered epidote bearing calcisilicate gneiss.

Psammitic Gneiss (unit 1e). These thin layers of calcareous gneiss have been included within unit 1e on all maps (see plates 7 and 16).

The rocks vary in texture depending on the mineralogy, but in general they are coarse grained and equigranular (see plate 8). The biotites in these rocks are sometimes skeletal, with potassium feldspar along the margins of the crystals (see plates 9 and 10). This is thought to be caused by the reaction of biotite with calcite and quartz to form potassium feldspar and hornblende. Hornblende is usually well crystallized and inclusion free. Diopside is occasionally found in the core of hornblende giving evidence to a reaction involving biotite plus quartz plus diopside, to produce potassium feldspar plus hornblende. Rarely, hornblende, diopside, quartz, and biotite are found together (see plate 11).

Chlorite is found in many calcsilicates, but is always a product of retrograde metamorphism. It can be found associated with either biotite or hornblende. When chlorite is found replacing biotite it shows dark green pleochroism and anomalous blue birefringence. When the chlorite is found associated with hornblende, it is usually found as radiating crystals inside or close to the hornblende (plate 12). Here it exhibits light green pleochroism and light grey birefringence. When chlorite is found with hornblende, calcite is often found close by, suggesting that calcite and chlorite may both form from the retrograde breakdown of hornblende.

Calcite is found in three different habits. The first is as discrete crystals, free from inclusions, and with sharp grain boundaries (plate 8), which are considered to be prograde calcite. The second is more inclusion-filled, and is always formed in association

Plate 7 Narrow band of calcsilicate gneiss within psammitic gneiss showing an open fold.

Plate 8 Sample B-263-73. 35X. Equilibrium mosaic texture of calcite-bearing calcsilicate gneiss. 1mm

Plate 9 Sample B-73-72. 100X. Potassium feldspar replacing biotite on the edge of the crystal.

0.1mm

Plate 10 Sample B-73-72. 100X. Same as above but with more complete replacement of biotite by potassium feldspar.

0.1mm

Plate 11 Sample B-164-73. 35X. Sample showing biotite-diopside-hornblende and quartz coexisting at one point. 1mm

Plate 12 Sample B-38-72. 35X. Sample showing retrograde reaction.
 $Hb \rightarrow Ch + Cc$ 1mm

with chlorite. It is interpreted to be a retrograde product of the breakdown of hornblende. The third type is formed along cracks and fractures, and alteration of other minerals is often associated with it. It is considered to be formed during a late, low temperature metamorphic event. No calcite has been considered to form part of the prograde assemblage if chlorite is found in the rock.

Epidote forms discrete euhedral crystals, with varying compositions as judged by a range in birefringence and pleochroism. The epidote always encloses zircon if zircon is present in the rock (plates 14 and 15). In some rocks, the epidote crystals have myrmekitic intergrowths of quartz (plate 13).

Scapolite is sometimes found in this unit but its occurrence is either associated with late alteration or with sulphide minerals.

More than one assemblage can often be found in the same thin section of this unit so care must be taken to insure that only minerals in close proximity are considered as assemblages.

Accessory minerals found in the calcsilicate rocks are apatite, sphene, zircon, Fe-Ti oxide, and sometimes pyrrhotite and pyrite.

I-5.5 Unit 1e. Psammitic Gneiss

The Psammitic Gneiss is a pink quartz-muscovite-microcline gneiss which is normally well-bedded and occasionally cross-bedded (plate 18). Magnetite-ilmenite layers are common (plate 17) and these layers sometimes show bedding and cross-bedding. The relative amounts of quartz-microcline and muscovite vary considerably, but the rock type almost always maintains its pink, bedded character. In places it is almost a pure quartzite with only minor muscovite and

Plate 13 Sample B-123-72. 35X. Myrmekitic intergrowths of quartz in epidote.

1mm

Plate 14 Sample B-773-73. 100X. Growth of epidote over zircons. The crystallographic outline of the epidote crystals outline those of zircon.

0.1mm

Plate 15 Sample B-773-73. 25X. Detailed view of epidote around zircon. Original (?) detrital zircon has euhedral overgrowth which has been overgrown by epidote. 01 mm

Plate 16 Outcrop of psammitic gneiss with layers of calcsilicate with orange calcite. From station B-237-73 on highway 533 west of Timber Lake.

Plate 17 Psammitic gneiss with ilmenite-magnetite layer which has been boudinaged, folded and injected by migmatite.

Plate 18 Psammitic gneiss showing folded cross-bedding along with a folded layer of migmatite. Dark bands are ilmenite rich layers. From station B-273-73 on highway 533 west of Timber Lake.

microcline. The Psammitic Gneiss is more quartz-rich in the northern part of the area, and near McLaren Point, more extensive areas of quartzite are found.

Along the Ontario Hydro transmission line near Cahill Lake, the muscovite has become unstable and is no longer a major constituent of the rock. Here the rock is a migmatitic quartz-potassium feldspar gneiss with varying amounts of plagioclase and kyanite (plate 19). The kyanite in these rocks is apple green and emerald green, and is often associated with the migmatitic layers. Biotite and garnet are sometimes found in this unit in the Cahill Lake Area; the small amounts of muscovite found in the Cahill Lake area are not associated with the rock fabric and are probably retrograde (plate 21). A few quartz pebbles are found in this unit in the Cahill Lake area (plate 20).

In general, the psammitic gneiss is coarse-grained, with a granoblastic texture. Plagioclase crystals are often full of inclusions and the microcline has well developed grid twinning. The microcline was X-rayed and proved to be a maximum microcline. A summary of the X-ray data is given in Table I-3. Triple junctions with 120° angles are typical (plate 22).

Accessory minerals are apatite and iron-oxides. Hematite flakes are found in the muscovite crystals.

I-5.6 Unit 1f: Amphibolite

The Amphibolite is found as layers within the psammitic gneiss and is most common in the Cahill Lake area. The rock is composed primarily of hornblende, plagioclase and garnet (plate 23).

Table I-3 X-RAY data for maximum microcline from sample
B-71-81.

$$a = 8.5595 \pm .0055$$

$$b = 12.9735 \pm .0055$$

$$c = 7.2165 \pm .0015$$

$$\alpha = 90.571 \pm .001$$

$$\beta = 115.908 \pm .001$$

$$\gamma = 87.786 \pm .001$$

$$V(\text{\AA}^3) = 720.276 \pm .492$$

Plate 19 Psammitic gneiss from the Cahill Lake area. Light areas are concentrations of kyanite, indicating that muscovite has broken down.

Plate 20 Conglomerate in psammitic gneiss near Cahill Lake. Pebbles are white quartzite and black quartzite. The black quartzite pebbles contain graphite. The rock has been migmatized.
From station B-379-73 on Map 3.

Plate 21 Sample B-417-73. 35X. Psammitic gneiss from the Cahill Lake area showing muscovite replacing kyanite. 1 mm

Plate 22 Sample B-71-14. 35X. Typical equilibrium mosaic texture of psammitic gneiss. 1 mm

Plate 23 Outcrop surface of para-amphibolite. White knots are plagioclase with kyanite in the cores. From station B-498-73 on Map 3.

Plate 24 Sample B-498-73. 10X. Kyanite crystal in amphibolite. Fine grained alteration surrounds kyanite which in turn is surrounded by plagioclase and biotite. 1mm

Quartz and biotite are present in trace amounts only. Whole rock analyses of this unit (Table 1-2) are comparable to aluminous basalts of the calc-alkaline suite. Thus the Amphibolite is interpreted at the present time as basaltic flows or sills.

In the area around Cahill Lake, kyanite is found in the Amphibolite. Long crystals of white kyanite up to 2 cm. in length can be seen protruding from the rock on the weathered surface. These kyanite crystals have been altered around the edges to a fibrous mineral which is surrounded in turn by plagioclase, biotite and finally hornblende (plate 24). In some cases the kyanite has been completely replaced by the plagioclase. The remainder of the rock is coarse-grained with garnet poikiloblasts up to 3 cm. in diameter, though they are normally less than 1 cm. in diameter. The minerals are all well crystallized with many 120° triple junctions. Accessory minerals are apatite, zircon and sphene.

I-5.7 Unit 2. The Antoine Gneiss

The Antoine Gneiss is a grey biotite-plagioclase gneiss which is migmatitic in places. These migmatized parts appear to be well layered (plates 25 and 26). The quartz content of this unit is usually less than 10 per cent but some varieties can contain more. The mafic content varies from 5 to 25 per cent, with the mafic mineral being biotite and/or hornblende. Feldspars make up the bulk of the rock with plagioclase predominating over potassium feldspar by a ratio of about 6:1. Muscovite is only rarely seen in this rock type, and then as a late retrograde or alteration product. Bedding is rarely seen. The rocks are coarse-grained with a granoblastic texture. Accessory minerals are apatite, zircon, sphene, and Fe-Ti oxides.

Plate 25 Typical exposure of Antoine Gneiss. Migmatitic biotite gneiss. From first outcrop on highway 533 north of Twist Lake.

Plate 26 Outcrop of migmatized biotite-oligoclase gneiss (Antoine Gneiss) with leucosome showing type 3 interference patterns. From outcrop on south side of highway 533 near northeast end of Timber Lake.

I-5.8 Unit 3. The Jocko Gneiss

The Jocko Gneiss is a meta-granite which has been intruded into the Antoine and Butler Gneisses. The meta-granites are pink in colour and well foliated (plate 27), usually with the fabric more pronounced near the margins of the body. Two planar fabrics have been recognized in this rock type where it outcrops along highway 533 west of Timber Lake. Where the Jocko Gneiss contains mafic minerals, they are hornblende, biotite and epidote. Calcite is also occasionally present.

All minerals have been completely recrystallized so the rock has a coarse-grained granoblastic texture. The igneous texture of the rock has been completely destroyed.

I-5.9 Unit 4.

The monzonitic rocks of Unit 4 are restricted to the southern part of the area. Most of these rocks are included within the Bonfield Batholith (see map 5) as described by Lumbers (1971). According to Lumbers (1971), this batholith contains rocks varying in composition from monzonitic to granitic. They are pink in colour and have a diagnostic mafic assemblage of biotite-garnet-hornblende, which is usually found in clusters. Foliation is observed in this unit only within one hundred feet of the contact. The mafic assemblage of this unit distinguishes it from the granites of the Jocko Gneiss. A few smaller bodies of this monzonite were found along highway 533, south of Harrington Lake and associated with the Jocko Gneiss and several small mafic intrusions.

Plate 27 Road cut exposure of Jocko Gneiss.
From station B-227-72 on Map 2.

Plate 28 Sample B-71-132. 10X. Coronite texture in metagabbro.

1mm

I-5.10 Unit 5

Two types of mafic plutonic rock are included within Unit 5. A meta-gabbro with corona textures and a meta-peridotite. Four separate bodies of the meta-gabbro were found: three along the Ottawa River between Bangs Bay and Coxey's Camp, and one west of highway 533 and south of Harrington Lake. They now contain spinel, clouded plagioclase, and olivine, hypersthene, diopside, garnet, biotite and ilmenite in corona textures (plates 28 and 29). The meta-gabbros are very similar to those described from the Adirondacks of New York State by Whitney and McLelland (1973). The corona textures are destroyed near the margins of the bodies where the rocks are foliated. Within the centre of bodies the corona texture is usually well preserved.

I-5.11 Unit 6

This unit is an unmetamorphosed quartz monzonite which is found just south of the Fournier River near Eldee on highway 63. It has not been studied in detail, but is coarse-grained and retains most of its primary igneous texture.

I-6 STRUCTURAL GEOLOGY

It was recognized during the first year of field work, that the structure of the Mattawa area was too complex to work out in detail while studying the petrology of the area. Some structural observations were made, however, and an interpretation is presented based on the data which are available.

Plate 29 Sample B-71-132. 35X. Close-up of plate 28 showing olivine core, surrounded in turn by hypersthene, clinopyroxene, clear plagioclase, and garnet. 1mm

The structural data collected were the orientations of the main planar features in the rock. The fabric measured in most cases was the foliation defined by planar minerals. In some outcrops two planar features could be seen, i.e., bedding and foliation, or sometimes two foliations. The most useful rock units for structural information are the Psammitic Gneiss and the Pyrrhotite Gneiss. The Psammitic Gneiss generally exhibits a well-developed foliation due to the alignment of platy minerals and may, in addition retain relic bedding. The Pyrrhotite Gneiss forms an excellent marker horizon. As a consequence of the lack of minor structure data, the following structural interpretation is based on outcrop patterns and foliation measurements.

A distinctive feature of Map 2 is the symmetry of the rock units on either side of the Pyrrhotite Gneiss. This is best illustrated near Crocan Lake and just north of the Dillow Lakes. This symmetry is maintained wherever this rock unit is found. The repetition of the sequence could either be caused by a refolded isoclinal fold or it could be caused by a repeated sedimentary sequence. It is suggested that this symmetry was produced by an early isoclinal fold and that the Pyrrhotite Gneiss is in the core of this fold, here designated as F_1 (see figure I-4). About one mile north-east of Crocan Lake, an F_1 closure is suspected. Such a closure would suggest that the symmetry of rock units is caused by a refolded recumbent isoclinal fold. While the actual F_1 closure was not observed in the field due to lack of outcrop, the Pyrrhotite Gneiss and Pelitic Gneiss are not present on the Quebec side of the Ottawa River while

10F |

Figure 1-4

Antoine Gneiss, Calcsilicate Gneiss and Psammitic Gneiss are present. No top determinations were found so the F_1 fold could be either anticlinal or synclinal. As the evidence suggests that the F_1 fold is a large nappe-like structure, and the cores of nappes usually contain the oldest rocks, the Pyrrhotite Gneiss, which is in the core of the F_1 fold is taken to be the oldest unit in the succession north of Crocan and the Dillow Lakes. On this basis, the stratigraphic sequence, from oldest to youngest, in the Timber Lake area is: Pyrrhotite Gneiss, Pelitic Gneiss, Calcsilicate Gneiss, Psammitic Gneiss and then the Antoine Gneiss. This group of lithologic units will subsequently be referred to as the Crocan Lake sequence.

From Crocan Lake, going northwest, the sequence is Pyrrhotite Gneiss, Pelitic Gneiss, Calcsilicate Gneiss and then the Antoine Gneiss. The Psammitic Gneiss is therefore missing between the Calcsilicate Gneiss and the Antoine Gneiss, according to the interpretation offered in the preceding paragraph. This inconsistency could be due to faulting. Northwest of Crocan Lake, the contact between the Calcsilicate Gneiss and the Antoine Gneiss is folded, so it is likely that the faulting, if present, was early in the structural history, and possibly during the first deformation event. This is often found to be the case in other mountain belts.

The foliation that has generally been measured in the field is possibly axial planar to the first phase of deformation since it has been folded by several subsequent events. It is not certain how many phases of deformation have affected the region after the development of F_1 but at least three are likely. Migmatites often show "type three" interference patterns as is illustrated on plate 26. If

the formation of the migmatites coincided with the culmination of metamorphism, then at least two deformation events must have subsequently taken place.

Between Timber Lake and Twist Lake, several large tight folds are observed. These folds repeat part of the Crocan Lake sequence. The first fold, which lies in the Antoine Gneiss and passes through the Dillow Lakes, is interpreted as an F_2 synform (see figure I-4). Just to the south, crossing the south Dillow Lake, is an antiform of Psammitic Gneiss and Pelitic Gneiss. Between the Psammitic Gneiss and the Pelitic Gneiss is a thin layer of Calcsilicate Gneiss which is too narrow to show on map 2. No Pyrrhotite Gneiss, however, is found. These folds are designated as F_2 folds on figure I-4 and the axial traces are parallel to F_1 as can be seen in figure I-4.

The axial trace of F_2 has also been folded and these folds are designated on figure I-4 as F_3 . The axial traces of F_3 trend northwest to the south of Timber Lake and north to northeast to the north of Timber Lake (see figure I-4). This divergence of F_3 axial traces can be explained by a late open folding, F_4 , with a northeast trending axis. A prominent example of F_4 is shown on figure I-4 with the trace of the axial plane crossing through Timber Lake.

The implications of the structural interpretation outlined above are summarized in figure I-6, a complete cross-section along line A-A', B-B' on figure I-4.

10F

Figure 1-6

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CROSS SECTION THROUGH CROCAN LA
-OF BUTLER GNEISS

- Granitic gneiss } JOCK
- Plagioclase-biotite gneiss } ANTO
- Amphibolite
- Psammitic gneiss
- Calcsilicate gneiss
- Pelitic gneiss
- Pyrrhotite gneiss } BUTL
- Trace of F4
- Trace of F2
- Trace of F1
- - - Geological contact

Kilometers
0 1/2
Miles

Vertical not to scale

Figure 1-6

CROSS SECTION THROUGH CROCAN LAKE SEQUENCE OF BUTLER GNEISS

Vertical not to scale

4 OF 4

I-7 STRATIGRAPHIC RELATIONSHIPS

The Crocan Lake sequence of the Butler Gneiss forms only part of the total thickness of Butler Gneiss. In the Cahill Lake area (maps 3 and 5) there is a thick sequence of Psammitic Gneiss with interlayered Amphibolite which is also part of the total Butler Gneiss unit. It will be referred to as the Cahill Lake sequence. It is not known what the stratigraphic thickness of the Cahill Lake sequence is but it covers about twice the area of the Crocan Lake sequence. As the structures of the rocks are roughly the same over the entire area, it is assumed that the Cahill Lake sequence of the Butler Gneiss is twice as thick as the Crocan Lake sequence. The Cahill Lake sequence could be either on top of or below the Crocan Lake sequence. Since the Antoine Gneiss is structurally above the Crocan Lake sequence, the Cahill Lake sequence is most easily interpreted as occurring below the Crocan Lake sequence.

A proposed stratigraphic column for the Butler Gneiss is shown on figure I-5. Near the base of the Cahill Lake sequence is a quartz pebble conglomerate (plate 20; see also map 3) which would be consistent with the suggestion that the Cahill Lake sequence represents the lower part of the Butler Gneiss.

The characteristics of the Pyrrhotite Gneiss change as it is traced northwards from Crocan Lake to the Grenville Front. For example, near Miner's Lake it contains up to 50 per cent sulphides while near Crocan Lake, the content of sulphides rarely exceeds 5 per cent. Also, a ten-foot-thick band of marble is found near Miner's Lake while none is found near Crocan Lake. Going further northwards from Miner's Lake to McLaren Point, which is fifteen miles southeast

of the Grenville Front, much thicker sequences of marble are associated with the iron formation, and in place of the Pyrrhotite Gneiss, a magnetite-silicate facies of iron formation is found. The Psammitic Gneiss also becomes progressively enriched in quartz towards the north. Thick sequences of quartzite are found near McLaren Point. This increasing maturity of sediments northwards suggests a possible shallowing of the basin in that direction.

On top of the Butler Gneiss is the Antoine Gneiss (figure I-5). Lumbers (1971a) has interpreted rocks that are mineralogically similar on the North Bay Sheet to be meta-greywackes. If the Antoine Gneiss is correctly interpreted as a sequence of greywackes, then the Butler Gneiss, has been succeeded by a deeper water facies, the Antoine Gneiss.

CHAPTER II METAMORPHIC PETROLOGY OF THE MATTAWA-JOCKO RIVER AREA

II-1 INTRODUCTION

The metamorphic petrology of three rock-types from the Mattawa-Jocko River area has been examined during this study. These are the Pelitic Gneiss, the Psammitic Gneiss and calcareous gneisses from various units within the stratigraphic succession. Marbles and assemblages from the Pyrrhotite Gneiss would also be useful but the rare occurrence of marble, and the weathered nature of the Pyrrhotite Gneiss make it difficult to study the metamorphic petrology of these two units.

The assemblages of the Pelitic Gneiss and Psammitic Gneiss can conveniently be represented on AFM diagrams (Thompson, 1957) and A^1KF diagrams (Winkler, 1967) respectively. However, the mineral assemblages from the calcareous gneiss cannot readily be represented on any commonly used two-dimensional diagrams. It has therefore been useful to develop an alternative two-dimensional projection as an aid in describing the petrology of the calcareous gneisses.

II-2 THE KAL PROJECTION

Minerals present in the calcsilicate rocks from Mattawa can be represented in the tetrahedron $Al_2O_3(A) - CaO(L) - KAlSi_3O_8(K) - MgO(M)$ as shown on figure II-1. The assumptions in the generation and use of this tetrahedron are the same as those discussed by Winkler

Figure II-1 ALKM tetrahedron showing positions of minerals found in calcsilicate rocks.

(1967). This diagram will be referred to as the ALKM tetrahedron. To use the ALKM tetrahedron, the components SiO_2 , CO_2 and H_2O are assumed to be present in excess as quartz and the fluid phase respectively, so that all assemblages shown in the tetrahedron must coexist with quartz and a fluid containing sufficient CO_2 and H_2O to stabilize the mineral assemblages. To use this tetrahedron as a means of describing phase relations, it would be necessary to visualize intersecting planes and volumes within the tetrahedron. Examination of figure II-1 suggests that projection from kyanite onto the KLM face or the projection from calcite onto the KAM face of the tetrahedron offers a convenient way of reducing phase relations onto a two-dimensional diagram. The phases, calcite or kyanite, however, are not present in sufficient rocks from Mattawa to make such projections of general use. The minerals, potassic feldspar, epidote, or biotite, also can serve as a basis for projection and because of its ubiquitous occurrence in calc-silicate rocks from Mattawa, biotite has been chosen as a projection point onto the KAL face of the tetrahedron.

For discussion of phase relations among end-member minerals, biotite can be assigned a unique composition and serves in the usual manner for minerals used as projecting points. In natural assemblages the Al content of biotite is variable and it was therefore necessary to decide on the most appropriate end-member biotite to represent natural assemblages. To calculate the positions of minerals on the KAL projection and to evaluate the effect of a moving projection point, the computer program PROKAL (appendix III) was written. The computer program relies

on the method of Greenwood (1975a) and uses matrix algebra to produce projections of phase relations. First the compositions of the projecting phases along with the components of the projection plane are written in terms of their oxide components as in matrix 1, table II-1. Next, the phases are written in terms of their components as in matrix 2, shown in table II-2. The solution matrix is produced by multiplying the inverse of matrix 1 by matrix 2. The resultant is shown as matrix 3 in table II-3 for the case in which phase relations are projected from phlogopite. As calcite is the only carbonate mineral and CO_2 is considered to be present in excess, the composition of calcite can be represented as CaO and CO_2 no longer shows up in the matrices. As phlogopite, quartz and water are in excess, they can be subtracted from the matrix, leaving the relative proportions of the components K, A, and L. For plotting purposes the values of K, A and L are recalculated in terms of the two ratios

$$\frac{K}{K + A + L} \quad \text{and} \quad \frac{L}{L + A}$$

A similar calculation has been carried out with the aluminous mica, eastonite, as the point of projection. The results of this calculation are summarized in matrix 4 of table III-4.

The positions of the minerals on the KAL projection calculated by the above method are shown for the projection from phlogopite on figure II-2, and for the projection from the aluminous biotite, eastonite, on figure II-3. Figures II-2 and II-3 illustrate the difficulties associated with projection from a mineral of variable

Table II-1 Matrix 1. Projecting phases written in terms of their oxide components.

	Kf	(Al ₂ O ₃)/2	CaO	MgO	SiO ₂	OH
Kf	1	0	0	0	0	0
(Al ₂ O ₃)/2	0	1	0	0	0	0
CaO	0	0	0	1	0	0
Ph	1	0	0	3	0	2
SiO ₂	0	0	0	0	1	0
OH	0	0	0	0	0	1

Table II-2 Matrix 2. Phases to be projected written in terms of their oxide components.

	Kf	(Al ₂ O ₃)/2	CaO	MgO	SiO ₂	OH
Ph	1	0	0	3	0	2
Kf	1	0	0	0	0	0
Mv	1	2	0	0	0	2
Cc	0	0	1	0	0	0
Zo	0	3	2	0	3	1
An	0	2	1	0	2	0
Ky	0	2	0	0	1	0
Tr	0	0	2	5	8	2
Di	0	0	1	1	2	0
Ch	0	2	0	5	3	8

Table II-3 Matrix 3. KAL matrix projected through phlogopite.

	K	A	L	Ph	SiO ₂	OH	$\frac{K}{K+A+L}$	$\frac{L}{L+A}$
Ph	0	0	0	1	0	0	1	-
Kf	1	0	0	0	0	0	1.0	0
Mv	1	1	0	0	-1	2	0.5	0
Cc	0	0	1	0	0	0	0	1.0
Zo	0	1.5	2	0	1.5	1.0	0	0.57
An	0	1.0	1.0	0	1.0	0	0	0.50
Ky	0	1.0	0	0	0	0	0	0
Tr	-1.667	0	2	1.667	8.00	-1.333	-5.0	1.0
Di	-0.333	0	1.0	0.333	2.0	-0.667	-0.50	1.0
Ch	-1.667	1.0	1.0	1.667	2.0	4.667		

Table II-4 Matrix 4. KAL matrix projected through eastonite.

	K	A	L	Ea	SiO ₂	OH	$\frac{K}{K+A+L}$	$\frac{L}{L+A}$
Ea	0	0	0	1.	0	0	-	-
Kf	1.	0	0	0	0	0	1.0	0
Mv	1.	1.	0	0	-1.	2.	0.5	0
Cc	0	0	1.	0	0	0	0	1.
Zo	0	1.5	2.	0	1.5	1.	0	0.57
An	0	1.	1.	0	1.	0	0	0.50
Ky	0	1.	0	0	0	0	0	1.
Tr	-2.	-0.5	2.0	2.	7.5	-2.		
Di	-0.4	-0.1	1.0	0.4	1.9	-8	-0.67	1.11
Ch	-2.	0.5	0	2.0	1.5	4.0

Figure II-2 KAL projection from phlogopite showing positions of minerals with end-member compositions.

Figure II-3 KAL projection from eastonite showing positions of minerals with end-member compositions.

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composition. In particular, the minerals tremolite, diopside, calcite and potassic feldspar are colinear on the projection from phlogopite but are not colinear when projected from eastonite. The effect of this is illustrated on figures II-4 and II-5 for some typical calcsilicate assemblages. Divariant fields for diopside - calcite - tremolite and diopside - potassic feldspar - calcite are not present in the projection from phlogopite (figure II-4) and are present in the projection from eastonite (figure II-5a). Another critical join that is affected by the change in projection point is the tremolite - muscovite join which cuts the zoisite - anorthite join on the projection from phlogopite (see figure II-4), but does not cut the zoisite - anorthite join on the projection from eastonite (figure II-5b).

To evaluate which biotite end-member to use in calculating a petrogenetic grid, the KAL projection has been calculated for natural assemblages from several areas with the results summarized on figure II-6 through II-8. The data for figures II-6 to II-8 are from this work, Carmichael (1970), Hewitt (1973), Thompson (1975) and Rice (in press). These diagrams indicate that the topologies derived from phlogopite as the point of projection are compatible with natural assemblages. Thus, projection from phlogopite is used subsequently in the construction of a petrogenetic grid with minerals having the idealized compositions shown on figure II-9.

II-3 CHEMICAL STUDY OF MINERALS IN ROCKS B-604-73 AND Y FROM MATTAWA

To plot the position of minerals found in the Mattawa area on the KAL projection, it was necessary to determine the exact com-

Figure II-4 KAL projection from phlogopite showing tie-lines which are dependent on the position of tremolite. The position of zoisite is shifted to a higher value of L in order to clarify the mineral relationships.

Figure II-5 KAL projections from eastonite illustrating the change in assemblages due to the change in the projection point.

a. illustrates that potassic feldspar, calcite and diopside are not colinear. b. illustrates that the muscovite-tremolite tie-line no longer cuts the zoisite-anorthite tie-line.

Figure II-6 KAL projection for rocks B-604-73 and Y from the Mattawa area.

Figure II-7 KAL projection for rocks from the Whetstone Lake area.
Data from Carmichael (1970).

Figure II-8. KAL projection for calcic amphiboles, diopside and dolomite, projected from their coexisting biotite. Data from Hewitt (1973), Thompson (1975) and Rice (in press).

Figure II-9 Idealized KAL projection from phlogopite. The position of Zo has been shifted to a higher value of L in order to illustrate more clearly the relationships among tremolite, zoisite, anorthite, muscovite and diopside.

position of the minerals. Two samples were chosen for study. Sample B-604-73 was chosen for the low variance of its assemblage, biotite - calcite - quartz - potassic feldspar - hornblende - plagioclase - epidote. Sample Y was chosen for the assemblage hornblende - plagioclase - kyanite - garnet - biotite - quartz, which has not been reported elsewhere in the Canadian Shield.

All of the coexisting minerals except quartz, calcite, kyanite, garnet, and accessories were analysed by P. Morton using a Cambridge Microscan 5 electron microprobe. The operating voltage was 15 Kv, and specimen current was 5×10^{-6} amps. The samples analysed were in the form of carbon-coated, polished thin sections. Standards used were native iron and analysed silicate minerals for elements other than iron. EMPADR VII (Rucklidge and Gasparrini, 1969), modified by D. H. Watkinson and W. Yzerdraat for the Carleton University computer, was used to process the data. The analyses with calculated structural formulae are shown on table II-5. The errors are believed to be within 5 percent of the reported values.

Zoning was absent in all minerals, including plagioclase, and the compositions of minerals were the same from one point of the thin section to another. As the minerals were also in textural equilibrium (see plate 22) it is assumed that the rocks analysed were in chemical equilibrium.

With microprobe analyses it is impossible to distinguish between iron in the ferrous state and iron in the ferric state. Some minerals such as epidote have iron almost entirely in the ferric state (Deer, et al., 1966; Dollase, 1973) so all of the iron in epidote is assumed to be ferric. Other minerals, such as biotite

Table II-5 Microprobe Analysis of Minerals from Samples B-604-73 and Y
(Values are in weight per cent of the oxides)

	Hornblende Sample B-604-73					Hornblende Sample Y				
	1A	1B	2A	2B	3	4A	4B	4C	5	
SiO ₂	40.75	40.01	39.64	39.74	39.53	42.56	42.79	42.60	42.40	
TiO ₂	0.80	1.07	1.03	1.06	1.11	0.82	1.05	0.89	0.95	
Al ₂ O ₃	13.44	14.01	14.27	14.52	14.48	16.81	16.68	17.08	16.84	
FeO	14.90	15.05	15.10	15.13	15.06	11.64	10.80	11.86	11.95	
Fe ₂ O ₃	4.14	4.18	4.20	4.20	4.19	12.33	12.91	12.29	12.30	
MgO	9.15	8.71	8.57	8.61	8.45	0.12	0.07	0.13	0.17	
MnO	0.42	0.40	0.41	0.41	0.41	11.35	11.23	11.30	11.48	
CaO	11.89	11.80	11.80	11.69	11.78	0.48	0.60	0.50	0.47	
K ₂ O	1.43	1.61	1.67	1.74	1.80	1.56	1.54	1.50	1.43	
Na ₂ O	0.95	0.93	0.94	0.95	0.98					
Total	97.87	97.77	97.63	98.05	97.79	97.67	97.67	98.15	97.99	

Table II-5 cont'd. Structural Formula of Hornblende Based on
23 Oxygen Atoms

	1A	1B	2A	2B	3
Si	6.160	6.070	6.031	6.018	6.008
Al	1.840	1.930	1.969	1.982	1.992
Al	0.554	0.576	0.591	0.610	0.602
Fe ³⁺	0.471	0.477	0.482	0.479	0.479
Mg	2.061	1.961	1.943	1.943	1.914
Mn	0.054	0.051	0.053	0.052	0.053
Ti	0.091	0.122	0.118	0.121	0.127
Fe ²⁺	1.769	1.813	1.814	1.795	1.825
Fe ²⁺	0.115	0.097	0.108	0.121	0.089
Ca	1.885	1.903	1.892	1.879	1.911
Ca	0.041	0.015	0.031	0.018	0.008
Na	0.278	0.273	0.278	0.278	0.349
K	0.276	0.312	0.324	0.337	0.289

Table II-5. cont'd. Structural Formula of Hornblende Based on
22 Oxygen Atoms

	4A	4B	4C	5
Si	6.154	6.194	6.164	6.154
Al	1.846	1.806	1.836	1.846
Al	1.036	1.040	1.076	1.036
Fe ³⁺	0.000	0.000	0.000	0.000
Mg	2.662	2.785	2.652	2.662
Mn	0.021	0.008	0.016	0.021
Ti	0.103	0.115	0.096	0.103
Fe ²⁺	1.178	1.052	1.160	1.778
Fe ²⁺	0.236	0.255	0.276	0.273
Ca	1.764	1.742	1.724	1.727
Ca	0.004	0.000	0.027	0.058
Na	0.439	0.433	0.422	0.401
K	0.089	0.110	0.092	0.087

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Table II-5 cont'd.

	Biotite Sample B-604-73			Biotite Sample Y	
	1	2	3	4	5
SiO ₂	35.92	35.55	35.44	37.12	37.18
TiO ₂	3.17	3.34	3.29	1.42	1.52
Al ₂ O ₃	16.04	16.17	16.36	19.05	18.70
FeO	15.74	15.40	15.57	11.33	11.14
Fe ₂ O ₃	4.37	4.28	4.33	-	-
MgO	11.47	11.43	11.26	17.74	17.23
MnO	0.28	0.26	0.29	0.07	0.07
CaO	0.00	0.00	0.00	0.00	0.00
BaO	0.50	0.48	0.43	n.d.	n.d.
Na ₂ O	0.07	0.07	0.06	0.50	0.46
K ₂ O	9.50	9.39	9.45	7.79	8.23
Total	97.06	96.37	96.48	95.02	94.53

Table II-5 cont'd. Structural Formulae of Biotite Based on
22 Oxygen Atoms

	1	2	3	4	5
Si	5.406	5.359	5.342	5.378	5.450
Al	2.594	2.641	2.658	2.622	2.550
Al	0.194	0.233	0.249	0.632	0.683
Ti	0.358	0.379	0.373	0.155	0.167
Fe ²⁺	1.981	1.941	1.962		
Fe ³⁺	0.495	0.486	0.431	1.373	1.366
Mg	2.572	2.568	2.530	3.830	3.765
Mn	0.035	0.034	0.037	0.009	0.009
Ca	0.000	0.000	0.000	0.000	0.000
Ba	0.030	0.028	0.025	n.d.	n.d.
Na	0.024	0.020	0.018	0.141	0.129
K	1.823	1.806	1.817	1.440	1.526

Table II-5 cont'd.

	Plagioclase Sample B-604-73				Plagioclase Sample Y			
	1	2A'(core)	2(edge)	3	4	5(edge)	5(core)	6
SiO ₂	59.93	59.68	59.88	59.41	57.38	56.97	58.20	57.18
Al ₂ O ₃	25.13	25.25	25.29	25.28	26.67	26.87	26.43	26.27
CaO	7.04	6.92	6.99	6.57	8.62	8.73	8.48	8.39
Na ₂ O	7.63	7.50	7.66	7.58	6.90	6.84	7.01	6.94
K ₂ O	0.23	0.23	0.22	0.21	0.05	0.05	0.06	0.06
FeO	0.11	0.06	0.06	0.07	0.03	0.03	0.03	0.03
Total	100.07	99.65	100.10	99.12	99.65	99.48	100.21	98.88

Table II-5 Cont'd. Structural Formulae of Plagioclase Based on 32 Oxygen Atoms

	1	2A(core)	2(edge)	3	4	5(edge)	5(core)	6
Si	10.687	10.676	10.671	10.675	10.322	10.271	10.400	10.361
Al	5.281	5.324	5.311	5.353	5.655	5.710	5.567	5.612
Ca	1.346	1.327	1.334	1.265	1.661	1.688	1.624	1.630
Na	2.637	2.600	2.646	2.642	2.405	2.390	2.428	2.438
K	0.052	0.053	0.051	0.047	0.012	0.012	0.014	0.013
Fe	0.016	0.010	0.009	0.011	0.004	0.004	0.005	0.005
Z	15.968	16.000	15.982	16.028	15.977	15.981	15.967	15.973
X	4.051	3.990	4.040	3.965	4.082	4.094	4.071	4.086
X _{An}	0.33	0.33	0.33	0.33	0.41	0.41	0.40	0.40
X _{Kf}	0.012	0.013	0.013	0.012	0.003	0.003	0.003	0.003

Table II-5 Cont'd Epidote Sample B-604-73

	1a	1b	1c	2	3
SiO ₂	37.71	38.00	37.35	38.15	37.39
TiO ₂	0.18	0.27	0.19	0.20	0.17
Al ₂ O ₃	25.77	25.31	24.92	25.78	25.83
Fe ₂ O ₃	10.25	10.64	10.72	10.29	9.99
MgO	0.08	0.09	0.07	0.04	0.07
MnO	0.14	0.16	0.15	0.18	0.21
CaO	23.79	23.67	23.42	23.69	23.23
Total	97.92	98.14	96.82	98.33	96.89

Table II-5 Cont'd Structural Formulae of Epidote Based on 25 Oxygen Atoms

	1a		1b		1c		2		3	
Si	5.946	6.000	5.987	6.000	5.967	6.000	5.984	6.000	5.959	6.000
Al	0.054		0.013		0.033		0.016		0.041	
Al	4.736	5.942	4.684	5.945	4.660	5.949	4.751	5.965	4.803	5.999
Fe ³⁺	1.216		1.261		1.289		1.214		1.196	
Ca	4.019		3.993		4.009		3.981		3.959	
Mn	0.018	4.076	0.032	4.068	0.023	4.068	0.024	4.038	0.028	4.023
Mg	0.018		0.021		0.016		0.009		0.016	
Ti	0.021		0.022		0.020		0.024		0.020	

and hornblende can have both ferric and ferrous iron in their structures.

As a first approximation it might be assumed that all of the iron in the hornblende and biotite is present in the ferrous state. However, whole-rock analyses of calcsilicate rocks have an average $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{FeO})$ ratio of 0.65 (table I-2) and from a rock similar to sample Y (sample Hb-Ky) the $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3 + \text{FeO})$ ratio is 0.10 (table I-2). For this reason it was felt that assuming a $\text{Fe}^{3+}/(\text{Fe}^{3+} + \text{Fe}^{2+})$ ratio of 0.20 for biotite and hornblende in rock B-604-73 was more reasonable than assuming that all iron was in the ferrous state. This assumed ferric/ferrous ratio is consistent with the structural formulae of biotite and hornblende based on 22 oxygen atoms and 23 oxygen atoms respectively.

Because of the low $\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ ratio of rock Y, all iron in the biotite and hornblende was assumed to be ferrous.

II-4 CRITICAL ASSEMBLAGES AND ISOGRADS IN THE MATTAWA AREA

Isograds, or changes in mineral assemblages not associated with changes in the bulk composition of the rock, can be related to specific mineral reactions as shown by Greenwood (1967), Carmichael (1970), Thompson (1973) and others. This approach was taken in studying the changes and differences in mineral assemblages observed in the Mattawa area. Minerals were identified by the study of thin sections, and minerals were considered to coexist if they were found in contact with one another, i.e. textural equilibrium. The assemblage data for all thin sections examined are listed in Appendix I.

II-4.1 Pelitic Gneiss

The only assemblage observed in the Pelitic Gneiss is biotite - garnet - kyanite - muscovite - quartz with tourmaline, plagioclase, apatite and opaques. This assemblage is shown on an AFM projection in figure II-10. No changes in this assemblage were observed except where migmatites were found. In the rocks of pelitic composition adjacent to migmatites, potassic feldspar was observed to coexist with all the minerals listed above. This relationship was not studied in detail.

II-4.2 Psammitic Gneiss

In the Crocan Lake area (maps 1, 2 and 5), the Psammitic Gneiss contains the assemblage muscovite - microcline - quartz - plagioclase with accessories. In the Cahill Lake area (maps 3 and 5), the Psammitic Gneiss contains the assemblage microcline - quartz - plagioclase - kyanite and accessories. Muscovite that is found in the Cahill Lake area with the kyanite - microcline - quartz assemblage is believed to be retrograde. The muscovite has no planar fabric, and is often seen replacing kyanite grains (see plate 21). Muscovite is never found with this habit in the Crocan Lake area. The coexistence of microcline - quartz - kyanite in the Cahill Lake area indicates that the Muscovite-out isograd has been surpassed. The Muscovite-out isograd must therefore exist between Cahill Lake and Crocan Lake, but it has not been precisely located due to difficult access to this region.

Figure II-10 AFM projection from muscovite showing phase relations in the Pelitic Gneiss.

II-4.3 Calcareous Gneisses

The mineral assemblages listed in table II-6 are observed in the calcareous gneisses from the Mattawa area. The regional distribution of the assemblages is shown on maps 6, 7 and 8 (in pocket). On map 6, the assemblage map of the Crocan Lake area, the most common assemblages are

1. Bi - Qz - Cc - Hb - Pf - Ep
2. Bi - Qz - Cc - Hb - Kf - Pf - Ep
3. Bi - Qz - Hb - Kf - Pf - Ep

In addition, the following two assemblages are rarely observed

5. Bi - Qz - Cc - Kf - Di - Pf - Ep
11. Bi - Qz - Di - Hb - Pf - Ep

Minerals from assemblages 1, 2, 3 can be related by the reaction

This reaction has been related to an isograd in the Whetstone Lake area by Carmichael (1970) in rocks containing the same minerals as assemblages 1, 2, and 3. Assemblage 1 correlates with the left-hand side of the reaction, assemblage 3 with the right-hand side and assemblage 2 contains all the minerals of the reaction.

An examination of mineral assemblages on map 6 does not suggest an obvious pattern that can be interpreted as an isograd. Approximately 1½ miles south of the mouth of the Jocko River, and in the area between Timber Lake and Crocan Lake, assemblages 1 and 2 do dominate over assemblage 3. These areas containing assemblages 1 and 2 are enclosed by areas containing assemblage 3 in a pattern

Table II-6 Mineral assemblages found in the calcareous gneisses of the Mattawa - North Bay - Temiscaming area.

Minerals Present	Symbol on Map	Assemblage #
Bi-Qz-Cc-Hb-Pf-Ep	○	1
Bi-Qz-Cc-Hb-Kf-Pf-Ep	●	2
Bi-Qz-Hb-Kf-Pf-Ep	●	3
Bi-Qz-Di-Kf-Pf-Ep	▲	4
Bi-Qz-Cc-Di-Kf-Pf-Ep	◐	5
Bi-Qz-Cc-Pf-Ep-Mv	◊	6
Bi-Qz-Cc-Kf-Pf-Ep-Mv	◑	7
Bi-Qz-Cc-Di-Hb-Pf-Ep	◼	8
Bi-Qz-Cc-Di-Pf-Ep	◕	9
Bi-Qz-Cc-Di-Hb-Kf-Pf-Ep	*	10
Bi-Qz-Di-Hb-Pf-Ep	△	11

that does not suggest regional gradients in intensive parameters.

Map 7 is the assemblage map for the Mattawa - North Bay Temiscaming area. Although map 7 covers a much larger area than map 6, the majority of samples contain assemblages 1, 2 and 3 as on map 6. Several widely scattered occurrences of some additional assemblages have been observed as follows

4. Bi - Qz - Kf - Di - Hb - Pf - Ep
6. Bi - Qz - Cc - Mv - Pf - Ep
7. Bi - Qz - Cc - Kf - Pf - Ep
8. Bi - Qz - Cc - Di - Hb - Pf - Ep

The only locality of assemblage 4 is about 1 mile west of Timber Lake on highway 533. Assemblage 6 is found about $1\frac{1}{2}$ miles west of Timber Lake on highway 533, and on a forest access road about 4 miles west of Temiscaming. Assemblage 7 is found about 1 mile west of Butler Lake on highway 63 and about 1 mile west of Timber Lake on highway 533. A sample of assemblage 8 was found about $\frac{1}{2}$ mile south of Timber Lake.

The scattered locations of the above-mentioned assemblages and the lack of any obvious pattern in the regional distribution of assemblages 1, 2 and 3 is similar to the distribution of assemblages on map 6. A similar pattern exists on map 8, the assemblage map for calcsilicates from Mattawa to the Grenville Front. Again, it is not possible to draw isograds that can be related to regional gradients in intensive parameters.

Idealized, end-member reactions such as

listed in table III-1, and correlating with assemblages 1, 2, and 3, are divariant. Considering the range of element substitution that can be accommodated in the minerals of calcsilicate rocks, it is likely that the reactions involving these minerals have a high variance, which could produce the complex pattern of mineral assemblages seen in the Mattawa area.

To evaluate the significance of mineral composition on the stability of mineral assemblages, the mineral analyses from table II-5 have been plotted on the KAL projection with the results shown on figure II-6. KAL projections such as shown on figure II-6 can be interpreted in the usual manner, provided that the composition of the projecting mineral remains constant for all assemblages plotted on the diagram. To evaluate the effect of the composition of biotite on the KAL projection, $K_2O - Al_2O_3 - FeO - MgO$, and $CaO - Al_2O_3 - FeO - MgO$ diagrams were plotted for sample B-604-73 from Mattawa and samples A110, A144, A500 and A545 from the Whetstone Lake area (Carmichael, 1970). The results are shown on figures II-11a and II-11b. It should be noted that the composition of the biotite for all assemblages is essentially constant, so the assemblages can be evaluated on the KAL projection. The relationships shown on figures II-6 and II-7 have been generalized and shown on figure II-12a. It is readily seen on figure II-12 that the minerals, potassic feldspar, calcite, amphibole, are not colinear. Thus, any reaction that may be involved in assemblages 1, 2, 3 cannot be represented by the simple, model reaction.

Figure II-11 KAF and ACF diagrams for rocks from the Mattawa area (B-604-73) and the Whetstone Lake area (110, 545, 500, 144).

Data for samples from Whetstone Lake area from Carmichael (1970).

Only the positions of hornblende and biotite are plotted. Note that except for sample Y, the composition of the biotites are essentially the same.

a.

b.

Figure II-12. Idealized KAL projections for rocks from the
Mattawa area, with biotites of a constant composition.

		Assemblage #
○	Bi - Qz - Cc - Hb - Pf - Ep	1
●	Bi - Qz - Cc - Hb - Kf - Pf - Ep	2
●	Bi - Qz - Hb - Kf - Pf - Ep	3
▲	Bi - Qz - Di - Kf - Pf - Ep	4
◐	Bi - Qz - Cc - Di - Kf - Pf - Ep	5
◊	Bi - Qz - Cc - Pf - Ep - Mv	6
◐	Bi - Qz - Cc - Kf - Pf - Ep - Mv	7
◑	Bi - Qz - Cc - Di - Hb - Pf - Ep	8
○	Bi - Qz - Cc - Di - Pf - Ep	9
*	Bi - Qz - Cc - Di - Hb - Kf - Pf - Ep	10
△	Bi - Qz - Di - Hb - Pf - Ep	11

Figure II-12 Idealized KAL diagram showing assemblages observed in the calc-silicate rocks from the Mattawa area.

The same conclusion was reached by Carmichael (1970) in a study of similar rocks from the Whetstone Lake area. Carmichael demonstrated that the minerals, epidote, plagioclase, sphene and iron oxide also participated in the actual reaction. Considering the complexity of the reaction, it would be anticipated that assemblage 2 from the Mattawa area would have a higher variance than the model reaction written above. Carmichael demonstrated that in the Whetstone Lake area, the effect of strong regional gradients in fluid composition dominated over other compositional variations in determining the pressure and temperature at which the reaction occurred. The development of an isograd in the Whetstone Lake area was apparently related to regional gradients in fluid composition as well as to gradients in pressure and temperature. The absence of an isograd in the area under study suggests that gradients in intensive parameters comparable to the Whetstone Lake area did not exist near Mattawa.

The interpretation of the metamorphic petrology of an area, in the past, has been based on the relationships among a series of isograds. This approach works best in an area of strong gradients in intensive parameters. For large segments of the Canadian Shield, which may lack gradients sufficient for the development of isograds on a local scale, an alternative approach is required. The approach that is developed in subsequent sections of this work is based on the solution of simultaneous equilibria that apply to an individual hand specimen rather than the mapping of isograds. Consider assemblage 2 (i.e., biotite - quartz - calcite - hornblende - potassic feldspar - plagioclase - epidote)

from the Mattawa area as an example. It is possible to write the following equilibria that constrain the conditions under which this equilibrium assemblage formed

With the assumption that the fluid phase consists of CO_2 and H_2O and that the activities of components dissolved in solids can be determined, then measured equilibrium constants for equilibria 1 and 26 can be solved simultaneously to obtain a univariant curve in PT space for assemblage 2. A number of additional equilibria constrain assemblage 2, including the iron analogue of equilibrium 1, equilibria involving additional components such as dissolved in iron oxides and sphene, and a variety of exchange equilibria involving components such as $\text{Fe}^{2+} - \text{Mg}$, $\text{Al} - \text{Fe}^{3+}$, $\text{OH} - \text{F}$ etc. Considering the limited experimental data that are available, it is possible to consider only equilibria 1 and 26 at present. Other specimens such as those containing assemblage 10 from table 11-6 can be even more closely constrained at present since the equilibrium

constrains this assemblage in addition to equilibria 1 and 26.

In order to attempt the approach of solving simultaneous equilibria for individual hand specimens, it is necessary to have an equilibrium model for the metamorphism of calcsilicate rocks. Such a model will be developed from available experimental data in the

subsequent chapter. The resulting model, along with experimental data pertinent to other rock types, will be applied to a discussion of the metamorphic petrology of the Mattawa area in Chapter IV.

CHAPTER III CALCULATED EQUILIBRIUM RELATIONSHIPS AMONG MINERAL ASSEMBLAGES

III-1 INTRODUCTION

Equilibrium relationships among eleven minerals, phlogopite, potassic feldspar, chlorite, tremolite, diopside, calcite, anorthite, zoisite, aluminosilicate and quartz can be quantitatively evaluated in the system $\text{CaO-MgO-SiO}_2\text{-Al}_2\text{O}_3\text{-KAlSi}_3\text{O}_8\text{-CO}_2\text{-H}_2\text{O}$ from equilibrium data for six independent reactions. Any six reactions for which data are available can be chosen provided they are algebraically independent.

III-2 THEORY

In considering the $\text{CaO-MgO-Al}_2\text{O}_3\text{-KAlSi}_3\text{O}_8\text{-SiO}_2\text{-H}_2\text{O-CO}_2$ system, two assumptions are made:

- 1) that quartz is always present in phase assemblages,
- 2) that H_2O and CO_2 are always present in excess.

With these assumptions, phase changes in the system can be illustrated by reference to the four components, $\text{CaO-MgO-KAlSi}_3\text{O}_8\text{-Al}_2\text{O}_3$.

If total pressure is held constant while temperature and the mole fraction of CO_2 (i.e., x_{CO_2}) are allowed to vary independently, then an invariant assemblage will, in the general case, contain six phases plus quartz and a fluid; a univariant assemblage will, in the general case, contain five minerals plus quartz and a fluid. Degeneracy among mineral compositions (Zen, 1966) will

result in fewer than five minerals being involved in an isobarically univariant reaction. The computer program COMBAL (see appendix IV) was written to find and balance all possible reactions among the minerals being studied. As the model system has quartz in excess, only those reactions which are compatible with the presence of quartz have been considered further. COMBAL produced 124 such reactions and these are listed in table III-1. The final 50 reactions listed in table III-1 are solid-solid reactions.

In the model being developed, phlogopite is always considered to be present, so the isobarically invariant assemblages must always contain phlogopite, except for certain degenerate cases. Isobarically invariant assemblages are listed in reciprocal notation in appendix II.

Equilibrium constants are written in terms of fugacities of the gas species, i.e., CO_2 , H_2O and the activities of the solids and liquids (i.e., B.C.N.M.). The equilibrium constant for the reaction

is then written as

$$K = \frac{(a_N)^n \cdot (a_M)^m \cdot (f_{\text{CO}_2})^x \cdot (f_{\text{H}_2\text{O}})^y}{(a_B)^b \cdot (a_C)^c} \quad 2$$

If N, M, B, and C are present in end-member phases, then the activity of each is taken to be unity, i.e., the standard states for these components are taken to be the pure mineral with the composition of the component at P and T.

Table III-1. Balanced Equilibria in the System
 $\text{CaO-MgO-KAlSi}_3\text{O}_8\text{-SiO}_2\text{-CO}_2\text{-H}_2\text{O}$

Reaction	Balanced Reaction	Reciprocal Notation
1	$5\text{Ph}+6\text{Cc}+24\text{Qz} = 5\text{Kf}+3\text{Tr}+6\text{CO}_2+\text{H}_2\text{O}$	(Mv, Ch, Di, An, Ky, Zo)
2	$\text{Tr}+3\text{Cc}+2\text{Qz} = 5\text{Di}+3\text{CO}_2+\text{H}_2\text{O}$	(Ph, Mv, Kf, Ch, An, Ky, Zo)
3	$\text{Mv}+\text{Qz} = \text{Kf}+\text{Ky}+\text{H}_2\text{O}$	(Ph, Ch, Tr, Di, Cc, An, Zo)
4	$\text{Mv}+\text{Cc}+2\text{Qz} = \text{Kf}+\text{An}+\text{CO}_2+\text{H}_2\text{O}$	(Ph, Ch, Tr, Di, Ky, Zo)
5	$\text{Mv}+2\text{Zo}+2\text{Qz} = \text{Kf}+4\text{An}+2\text{H}_2\text{O}$	(Ph, Ch, Tr, Di, Cc, Ky)
6	$5\text{Mv}+3\text{Ch} = 5\text{Ph}+8\text{Ky}+\text{Qz}+12\text{H}_2\text{O}$	(Kf, Di, Tr, Cc, An, Zo)
7	$9\text{Ch}+50\text{Di}+43\text{Qz} = 19\text{Tr}+6\text{Zo}+14\text{H}_2\text{O}$	(Ph, Mv, Kf, Cc, An, Ky)
8	$\text{Ch}+5\text{Di}+5\text{Qz} = 2\text{Tr}+\text{An}+2\text{H}_2\text{O}$	(Ph, Mv, Kf, Cc, Ky, Zo)
9	$3\text{Ch}+10\text{Di}+14\text{Qz} = 5\text{Tr}+3\text{Ky}+7\text{H}_2\text{O}$	(Ph, Mv, Kf, Cc, An, Zo)
10	$\text{Ch}+12\text{Zo}+9\text{Qz} = 5\text{Di}+19\text{An}+10\text{H}_2\text{O}$	(Ph, Mv, Kf, Tr, Cc, Ky)
11	$4\text{Ch}+10\text{Zo}+17\text{Qz} = 20\text{Di}+19\text{Ky}+21\text{H}_2\text{O}$	(Ph, Mv, Kf, Tr, Cc, An)
12	$\text{Ch}+6\text{Zo}+7\text{Qz} = \text{Tr}+10\text{An}+6\text{H}_2\text{O}$	(Ph, Mv, Kf, Di, Cc, Ky)
13	$2\text{Ch}+2\text{Zo}+9\text{Qz} = 2\text{Tr}+5\text{Ky}+7\text{H}_2\text{O}$	(Ph, Mv, Kf, Di, Cc, An)
14	$\text{Ch}+5\text{An}+3\text{Qz} = 5\text{Di}+6\text{Ky}+4\text{H}_2\text{O}$	(Ph, Mv, Kf, Tr, Cc, Zo)
15	$\text{Ch}+2\text{An}+4\text{Qz} = \text{Tr}+2\text{Ky}+3\text{H}_2\text{O}$	(Ph, Mv, Kf, Di, Cc, Zo)
16	$3\text{Ch}+19\text{Cc}+27\text{Qz} = 15\text{Di}+2\text{Zo}+19\text{CO}_2+11\text{H}_2\text{O}$	(Ph, Mv, Kf, Tr, An, Ky)
17	$\text{Ch}+6\text{Cc}+9\text{Qz} = 5\text{Di}+\text{An}+6\text{CO}_2+4\text{H}_2\text{O}$	(Ph, Mv, Kf, Tr, Ky, Zo)
18	$\text{Ch}+5\text{Cc}+8\text{Qz} = 5\text{Di}+\text{Ky}+5\text{CO}_2+4\text{H}_2\text{O}$	(Ph, Mv, Kf, Tr, An, Zo)
19	$3\text{Ch}+10\text{Cc}+21\text{Qz} = 3\text{Tr}+2\text{Zo}+10\text{CO}_2+8\text{H}_2\text{O}$	(Ph, Mv, Kf, Di, An, Ky)
20	$\text{Ch}+3\text{Cc}+7\text{Qz} = \text{Tr}+\text{An}+3\text{CO}_2+3\text{H}_2\text{O}$	(Ph, Mv, Kf, Di, Ky, Zo)
21	$\text{Ch}+2\text{Cc}+6\text{Qz} = \text{Tr}+\text{Ky}+2\text{CO}_2+3\text{H}_2\text{O}$	(Ph, Mv, Kf, Di, An, Zo)
22	$4\text{Tr}+6\text{Zo} = 20\text{Di}+9\text{Ky}+\text{Qz}+7\text{H}_2\text{O}$	(Ph, Mv, Kf, Ch, Cc, An)
23	$\text{Tr}+6\text{Zo}+2\text{Qz} = 5\text{Di}+9\text{An}+4\text{H}_2\text{O}$	(Ph, Mv, Kf, Ch, Cc, Ky)
24	$\text{Tr}+3\text{An} = 5\text{Di}+3\text{Ky}+\text{Qz}+\text{H}_2\text{O}$	(Ph, Mv, Kf, Ch, Cc, Zo)
25	$2\text{Zo}+\text{Ky}+\text{Qz} = 4\text{An}+\text{H}_2\text{O}$	(Ph, Mv, Kf, Ch, Tr, Di, Cc)

- 26 $3\text{An} + \text{Cc} + \text{H}_2\text{O} = 2\text{Zo} + \text{CO}_2$ (Ph, Mv, Kf, Ch, Tr, Di, Ky, Qz)
- 27 $3\text{Ky} + 4\text{Cc} + 3\text{Qz} + \text{H}_2\text{O} = 2\text{Zo} + 4\text{CO}_2$ (Ph, Mv, Kf, Ch, Tr, Di, An)
- 28 $\text{Ky} + \text{Cc} + \text{Qz} = \text{An} + \text{CO}_2$ (Ph, Mv, Kf, Ch, Tr, Di, Zo)
- 29 $3\text{Ph} + 3\text{Ch} + 16\text{Di} + 23\text{Qz} = 3\text{Mv} + 8\text{Tr} + 4\text{H}_2\text{O}$ (Kf, Cc, An, Ky, Zo)
- 30 $\text{Ph} + \text{Ch} + 8\text{Cc} + 13\text{Qz} = \text{Mv} + 8\text{Di} + 8\text{CO}_2 + 4\text{H}_2\text{O}$ (Kf, Tr, An, Ky, Zo)
- 31 $5\text{Ph} + 5\text{Ch} + 16\text{Cc} + 49\text{Qz} = 5\text{Mv} + 8\text{Tr} + 16\text{CO}_2 + 12\text{H}_2\text{O}$ (Kf, Di, An, Ky, Zo)
- 32 $\text{Ph} + 6\text{Zo} + 6\text{Qz} = \text{Kf} + 3\text{Di} + 9\text{An} + 4\text{H}_2\text{O}$ (Mv, Ch, Tr, Cc, Ky)
- 33 $4\text{Ph} + 6\text{Zo} + 15\text{Qz} = 4\text{Kf} + 12\text{Di} + 9\text{Ky} + 7\text{H}_2\text{O}$ (Mv, Ch, Tr, Cc, An)
- 34 $5\text{Ph} + 12\text{Zo} + 24\text{Qz} = 5\text{Kf} + 3\text{Tr} + 18\text{An} + 8\text{H}_2\text{O}$ (Mv, Ch, Di, Cc, Ky)
- 35 $10\text{Ph} + 6\text{Zo} + 39\text{Qz} = 10\text{Kf} + 6\text{Tr} + 9\text{Ky} + 7\text{H}_2\text{O}$ (Mv, Ch, Di, Cc, An)
- 36 $\text{Ph} + 4\text{Zo} + 4\text{Qz} = \text{Mv} + 3\text{Di} + 5\text{An} + 2\text{H}_2\text{O}$ (Kf, Ch, Tr, Cc, Ky)
- 37 $3\text{Ph} + 2\text{Zo} + 5\text{Cc} + 12\text{Qz} = 3\text{Mv} + 9\text{Di} + 5\text{CO}_2 + \text{H}_2\text{O}$ (Kf, Ch, Tr, An, Ky)
- 38 $\text{Ph} + 3\text{An} + 3\text{Qz} = \text{Kf} + 3\text{Di} + 3\text{Ky} + \text{H}_2\text{O}$ (Mv, Ch, Tr, Cc, Zo)
- 39 $5\text{Ph} + 6\text{An} + 18\text{Qz} = 5\text{Kf} + 3\text{Tr} + 6\text{Ky} + 2\text{H}_2\text{O}$ (Mv, Ch, Di, Cc, Zo)
- 40 $\text{Ph} + \text{An} + 2\text{Cc} + 4\text{Qz} = \text{Mv} + 3\text{Di} + 2\text{CO}_2$ (Kf, Ch, Tr, Ky, Zo)
- 41 $5\text{Ph} + 5\text{An} + \text{Cc} + 14\text{Qz} + 3\text{H}_2\text{O} = 5\text{Mv} + 3\text{Tr} + \text{CO}_2$ (Kf, Ch, Di, Ky, Zo)
- 42 $\text{Ph} + \text{Ky} + 3\text{Cc} + 5\text{Qz} = \text{Mv} + 3\text{Di} + 3\text{CO}_2$ (Kf, Ch, Tr, An, Zo)
- 43 $5\text{Ph} + 5\text{Ky} + 6\text{Cc} + 19\text{Qz} + 3\text{H}_2\text{O} = 5\text{Mv} + 3\text{Tr} + 6\text{CO}_2$ (Kf, Ch, Di, An, Zo)
- 44 $\text{Ph} + 3\text{Cc} + 6\text{Qz} = \text{Kf} + 3\text{Di} + 3\text{CO}_2 + \text{H}_2\text{O}$ (Mv, Ch, Tr, An, Ky, Zo)
- 45 $8\text{Kf} + 3\text{Ch} = 5\text{Ph} + 3\text{Mv} + 9\text{Qz} + 4\text{H}_2\text{O}$ (Tr, Di, Cc, An, Ky, Zo)
- 46 $19\text{Kf} + 9\text{Ch} + 12\text{Di} = 19\text{Ph} + 6\text{Zo} + 33\text{Qz} + 14\text{H}_2\text{O}$ (Mv, Tr, Cc, An, Ky)
- 47 $2\text{Kf} + \text{Ch} + \text{Di} = 2\text{Ph} + \text{An} + 3\text{Qz} + 2\text{H}_2\text{O}$ (Mv, Tr, Cc, Ky, Zo)
- 48 $25\text{Kf} + 9\text{Ch} + 6\text{Tr} = 25\text{Ph} + 6\text{Zo} + 57\text{Qz} + 14\text{H}_2\text{O}$ (Mv, Di, Cc, An, Ky)
- 49 $5\text{Kf} + 2\text{Ch} + \text{Tr} = 5\text{Ph} + 2\text{An} + 10\text{Qz} + 4\text{H}_2\text{O}$ (Mv, Di, Cc, Ky, Zo)
- 50 $5\text{Kf} + 3\text{Ch} + 6\text{Zo} = 5\text{Ph} + 12\text{An} + 3\text{Qz} + 10\text{H}_2\text{O}$ (Mv, Di, Tr, Cc, Ky)
- 51 $5\text{Kf} + 3\text{Ch} + 4\text{Cc} = 5\text{Ph} + 2\text{Zo} + 3\text{Qz} + 4\text{CO}_2 + 6\text{H}_2\text{O}$ (Mv, Di, Tr, An, Ky)
- 52 $5\text{Kf} + 3\text{Ch} + 3\text{Cc} = 5\text{Ph} + 3\text{An} + 3\text{Qz} + 3\text{CO}_2 + 7\text{H}_2\text{O}$ (Mv, Di, Tr, Ky, Zo)

- 53 $Kf+3Tr+6Cc = Ph+12Di+6CO_2+2H_2O$ (Mv, Ch, An, Ky, Zo, Qz)
- 54 $5Kf+3Ch = 5Ph+3Ky+6Qz+7H_2O$ (Mv, Di, Tr, Cc, An, Zo)
- 55 $19Mv+5Ch+32Di = 19Ph+16Zo+31Qz+12H_2O$ (Kf, Tr, Cc, An, Ky)
- 56 $3Mv+Ch+4Di = 3Ph+4An+3Qz+4H_2O$ (Kf, Tr, Cc, Ky, Zo)
- 57 $15Mv+Ch+8Tr = 15Ph+16An+35Qz+12H_2O$ (Kf, Di, Cc, Ky, Zo)
- 58 $5Mv+3Ch+16Zo+7Qz = 5Ph+32An+20H_2O$ (Kf, Di, Tr, Cc, Ky)
- 59 $15Mv+9Ch+32Cc+21Qz = 15Ph+16Zo+32CO_2+28H_2O$ (Kf, Di, Tr, An, Ky)
- 60 $5Mv+3Ch+8Cc+7Qz = 5Ph+8An+8CO_2+12H_2O$ (Kf, Di, Tr, Ky, Zo)
- 61 $9Mv+Kf+6Tr = 10Ph+6Zo+30Qz+2H_2O$ (Ch, Di, Cc, An, Ky)
- 62 $9Mv+12Di = 4Ph+5Kf+6Zo+6Qz+2H_2O$ (Ch, Tr, Cc, An, Ky)
- 63 $3Mv+3Di = Ph+2Kf+3An+2H_2O$ (Ch, Tr, Cc, Ky, Zo, Qz)
- 64 $6Mv+3Tr = 5Ph+Kf+6An+12Qz+4H_2O$ (Ch, Di, Cc, Ky, Zo)
- 65 $25Mv+16Tr = 25Ph+Ch+16Zo+77Qz+4H_2O$ (Kf, Di, Cc, An, Ky)
- 66 $Mv+Tr = Ph+2Di+Ky+3Qz+H_2O$ (Kf, Ch, Cc, An, Zo)
- 67 $5Mv+3Tr = 5Ph+2Zo+2An+14Qz+2H_2O$ (Kf, Ch, Di, Cc, Ky)
- 68 $10Mv+6Tr = 10Ph+6Zo+Ky+29Qz+3H_2O$ (Kf, Ch, Di, Cc, An)
- 69 $9Mv+5Tr+2Di = 9Ph+6Zo+26Qz+2H_2O$ (Kf, Ch, Cc, An, Ky)
- 70 $5Mv+3Tr+Ky = 5Ph+6An+13Qz+3H_2O$ (Kf, Ch, Di, Cc, Zo)
- 71 $15Mv+9Tr+2Cc = 15Ph+10Zo+42Qz+2CO_2+4H_2O$ (Kf, Ch, Di, An, Ky)
- 72 $3Mv+4Cc+6Qz = 3Kf+2Zo+4CO_2+2H_2O$ (Ph, Ch, Di, Tr, An, Ky)
- 73 $4Ph+6Zo+11Qz = 4Mv+12Di+5Ky+3H_2O$ (Kf, Ch, Tr, Cc, An)
- 74 $3Mv+2Tr = 3Ph+Di+3An+8Qz+2H_2O$ (Kf, Ch, Cc, Ky, Zo)
- 75 $Ph+2Di+4Qz = Kf+Tr$ (Mv, Ch, Cc, An, Ky, Zo, Fl)
- 76 $Ph+An+2Qz = Mv+3Di+2Ky$ (Kf, Ch, Tr, Cc, Zo, Fl)
- 77 $5Ph+7Mv+13Qz = 12Kf+3Ch+4Ky$ (Tr, Di, Cc, An, Zo, Fl)
- 78 $Tr+6Zo+6Ky = Ch+14An+Qz$ (Ph, Kf, Mv, Di, Cc, Fl)
- 79 $15Di+2Ch+7An+8Qz = 5Tr+6Zo$ (Ph, Kf, Mv, Ky, Cc, Fl)
- 80 $10Di+Ch+2Ky+5Qz = 3Tr+2Zo$ (Ph, Kf, Mv, An, Cc, Fl)
- 81 $15Di+Ch+6Ky+7Qz = 4Tr+7An$ (Ph, Kf, Mv, Cc, Zo, Fl)

82	$5\text{Di}+2\text{Zo}+4\text{Ky}+2\text{Qz} = \text{Tr}+7\text{An}$	(Ph, Kf, Mv, Ch, Cc, Fl)
83	$5\text{Di}+8\text{Zo}+10\text{Ky}+\text{Qz} = \text{Ch}+21\text{An}$	(Ph, Kf, Mv, Tr, Cc, Fl)
84	$\text{Ph}+3\text{Mv}+2\text{Di}+3\text{Qz} = 4\text{Kf}+\text{Ch}+2\text{An}$	(Tr, Cc, Ky, Zo, Fl)
85	$5\text{Ph}+5\text{Mv}+4\text{Zo}+13\text{Qz} = 10\text{Kf}+3\text{Ch}+8\text{An}$	(Tr, Di, Ky, Cc, Fl)
86	$\text{Ph}+\text{Kf}+2\text{Zo}+2\text{Qz} = 2\text{Mv}+3\text{Di}+\text{An}$	(Tr, Ch, Ky, Cc, Fl)
87	$4\text{Ph}+3\text{Kf}+6\text{Zo}+8\text{Qz} = 7\text{Mv}+12\text{Di}+2\text{Ky}$	(Tr, Ch, An, Cc, Fl)
88	$\text{Ph}+6\text{Kf}+\text{Ch}+4\text{Zo}+\text{Qz} = 7\text{Mv}+8\text{Di}$	(Tr, An, Ky, Cc, Fl)
89	$5\text{Ph}+2\text{Kf}+\text{Ch}+4\text{Zo}+17\text{Qz} = 7\text{Mv}+4\text{Tr}$	(Di, An, Ky, Cc, Fl)
90	$5\text{Ph}+4\text{Zo}+16\text{Qz} = 4\text{Mv}+\text{Kf}+3\text{Tr}+2\text{An}$	(Di, Ch, Ky, Cc, Fl)
91	$10\text{Ph}+6\text{Zo}+32\text{Qz} = 7\text{Mv}+3\text{Kf}+6\text{Tr}+2\text{Ky}$	(Ch, Di, An, Cc, Fl)
92	$7\text{Ph}+8\text{Zo}+15\text{Qz} = 7\text{Mv}+\text{Ch}+16\text{Di}+4\text{Ky}$	(Kf, Tr, An, Cc, Fl)
93	$5\text{Ph}+8\text{Zo}+11\text{Qz} = 5\text{Mv}+\text{Ch}+10\text{Di}+6\text{An}$	(Kf, Tr, Ky, Cc, Fl)
94	$2\text{Ph}+2\text{Zo}+6\text{Qz} = 2\text{Mv}+\text{Tr}+\text{Di}+\text{An}$	(Kf, Ch, Ky, Cc, Fl)
95	$7\text{Ph}+6\text{Zo}+20\text{Qz} = 7\text{Mv}+3\text{Tr}+6\text{Di}+2\text{Ky}$	(Kf, Ch, An, Cc, Fl)
96	$5\text{Ph}+6\text{Zo}+12\text{Qz} = 5\text{Kf}+2\text{Ch}+5\text{Di}+7\text{An}$	(Mv, Tr, Cc, Ky, Fl)
97	$3\text{Ph}+2\text{Zo}+7\text{Qz} = 3\text{Kf}+\text{Ch}+4\text{Di}+2\text{Ky}$	(Mv, Tr, Cc, An, Fl)
98	$15\text{Ph}+12\text{Zo}+44\text{Qz} = 15\text{Kf}+4\text{Ch}+5\text{Tr}+14\text{An}$	(Mv, Di, Cc, Ky, Fl)
99	$5\text{Ph}+2\text{Zo}+15\text{Qz} = 5\text{Kf}+\text{Ch}+2\text{Tr}+2\text{Ky}$	(Mv, Di, Cc, An, Fl)
100	$5\text{Ph}+6\text{An}+16\text{Qz} = 2\text{Mv}+3\text{Kf}+3\text{Tr}+4\text{Ky}$	(Ch, Di, Cc, Zo, Fl)
101	$4\text{Ph}+7\text{An}+9\text{Qz} = 4\text{Kf}+\text{Ch}+7\text{Di}+6\text{Ky}$	(Mv, Tr, Cc, Zo, Fl)
102	$\text{Ph}+7\text{An}+2\text{Qz} = \text{Kf}+3\text{Di}+2\text{Zo}+4\text{Ky}$	(Mv, Ch, Tr, Cc, Fl)
103	$5\text{Ph}+14\text{An}+16\text{Qz} = 5\text{Kf}+3\text{Tr}+4\text{Zo}+8\text{Ky}$	(Mv, Ch, Di, Cc, Fl)
104	$15\text{Ph}+14\text{An}+46\text{Qz} = 15\text{Kf}+2\text{Ch}+7\text{Tr}+12\text{Ky}$	(Mv, Di, Zo, Cc, Fl)
105	$15\text{Ph}+\text{Ch}+12\text{Zo}+49\text{Qz} = 15\text{Mv}+10\text{Tr}+4\text{An}$	(Kf, Di, Cc, Ky, Fl)
106	$35\text{Ph}+3\text{Ch}+24\text{Zo}+115\text{Qz} = 35\text{Mv}+24\text{Tr}+4\text{Ky}$	(Kf, Di, An, Cc, Fl)
107	$5\text{Ph}+\text{Ch}+8\text{An}+17\text{Qz} = 5\text{Mv}+4\text{Tr}+4\text{Ky}$	(Kf, Di, Cc, Zo, Fl)
108	$5\text{Ph}+24\text{Zo}+20\text{Ky}+13\text{Qz} = 5\text{Mv}+3\text{Ch}+48\text{An}$	(Kf, Tr, Di, Cc, Fl)
109	$5\text{Ph}+6\text{Zo}+2\text{Ky}+16\text{Qz} = 5\text{Mv}+3\text{Tr}+6\text{An}$	(Kf, Ch, Di, Cc, Fl)

110	$5\text{Ph}+14\text{Zo}+10\text{Ky}+13\text{Qz} = 5\text{Kf}+3\text{Ch}+28\text{An}$	(Mv, Tr, Di, Cc, Fl)
111	$7\text{Ph}+\text{Ch}+4\text{Di}+4\text{Zo}+25\text{Qz} = 7\text{Mv}+6\text{Tr}$	(Kf, Cc, An, Ky, Fl)
112	$3\text{Ph}+\text{Ch}+6\text{Di}+2\text{An}+13\text{Qz} = 3\text{Mv}+4\text{Tr}$	(Kf, Cc, Ky, Zo, Fl)
113	$7\text{Ph}+3\text{Ch}+24\text{Di}+4\text{Ky}+35\text{Qz} = 7\text{Mv}+12\text{Tr}$	(Kf, Cc, An, Zo, Fl)
114	$7\text{Mv}+5\text{Tr} = 7\text{Kf}+3\text{Ch}+10\text{Di}+4\text{Ky}+7\text{Qz}$	(Ph, An, Cc, Zo, Fl)
115	$7\text{Mv}+2\text{Tr} = 7\text{Kf}+2\text{Ch}+2\text{Zo}+2\text{Ky}+2\text{Qz}$	(Ph, Di, Ac , Cc, Fl)
116	$3\text{Mv}+\text{Tr} = 3\text{Kf}+\text{Ch}+2\text{An}+\text{Qz}$	(Ph, Di, Cc, Ky, Zo, Fl)
117	$\text{Mv}+4\text{An} = \text{Kf}+2\text{Zo}+2\text{Ky}$	(Ph, Ch, Tr, Di, Cc, Qz, Fl)
118	$7\text{Mv}+10\text{Di}+3\text{Qz} = 7\text{Kf}+\text{Ch}+\text{Tr}+4\text{Zo}$	(Ph, An, Cc, Ky, Fl)
119	$5\text{Mv}+5\text{Di}+\text{Qz} = 5\text{Kf}+\text{Ch}+2\text{Zo}+\text{An}$	(Ph, Tr, Cc, Ky, Fl)
120	$21\text{Mv}+20\text{Di}+4\text{Qz} = 21\text{Kf}+4\text{Ch}+10\text{Zo}+2\text{Ky}$	(Ph, Tr, Cc, An, Fl)
121	$2\text{Mv}+5\text{Di}+\text{An}+2\text{Qz} = 2\text{Kf}+\text{Tr}+2\text{Zo}$	(Ph, Ch, Cc, Ky, Fl)
122	$7\text{Mv}+20\text{Di}+2\text{Ky}+8\text{Qz} = 7\text{Kf}+4\text{Tr}+6\text{Zo}$	(Ph, Ch, Cc, An, Fl)
123	$\text{Mv}+5\text{Di}+2\text{Ky}+2\text{Qz} = \text{Kf}+\text{Tr}+3\text{An}$	(Ph, Ch, Cc, Zo, Fl)
124	$4\text{Mv}+5\text{Di}+2\text{Ky}+\text{Qz} = 4\text{Kf}+\text{Ch}+5\text{An}$	(Ph, Tr, Cc, Zo, Fl)

Equation 2 then reduces to

$$K = (f_{\text{CO}_2})^x \cdot (f_{\text{H}_2\text{O}})^y \quad 3$$

The equilibrium constant, K , of a reaction is often expressed to sufficient accuracy by the relationship (for example, Skippen, 1975).

$$\ln K = \frac{-\Delta H_r}{RT} + \frac{\Delta S_r}{R} - \frac{\Delta V_s (P_2 - P_1)}{RT} \quad 4$$

where ΔH_r is the mean enthalpy of reaction in the temperature range of interest, ΔS_r is the mean entropy of reaction in the temperature range of interest, and ΔV_s is the change in molar volumes of the solids during the reaction. Equation 4 is rewritten as

$$\log K = \frac{A}{T} + B + \frac{C(P - 2000)}{T} \quad 5$$

where $A = \frac{-\Delta H_r}{2.303R}$ 6

$$B = \frac{\Delta S_r}{2.303R} \quad 7$$

$$C = \frac{-\Delta V_s^0}{2.303R} \quad 8$$

A and B can be determined by experiment and C is calculated from molar volume data. It is convenient to present

experimental results in this form because of the linear relationship between the logarithm of the equilibrium constant and the Gibbs free-energy change of a reaction. This relationship allows the additivity of free energy changes for a series of chemical relations to be carried over to the experimental data. In this way it is possible to calculate the equilibrium constants of reactions which are linear combinations of experimentally determined reactions.

III-3 EVALUATION OF EXPERIMENTAL DATA

A method for testing the consistency of experimental data was developed to help determine which independent experimental reactions to use in the construction of a petrogenetic grid for minerals in the Mattawa area. This test involved the calculation of a standard enthalpy of reaction of the solids for each experimental point on a reversed reaction.

Again, considering the reaction

then

$$\Delta G_{r,s}(T_e, P_e) + \Delta G_{f,CO_2}^*(T_e, P_e) + \Delta G_{f,H_2O}(T_e, P_e) = 0 \quad 9$$

where $\Delta G_{r,s}$ is the Gibbs free energy change for the solids in the reaction. For one mole of each phase,

$$\Delta G_f(T_e, P_e) = \Delta G_f^0(298, 1) - \int_{298}^{T_e} \Delta S_f(T) dT + \int_1^{P_e} \Delta V_f(P) dP \quad 10$$

Combining equation 10 with equation 9 gives

$$\begin{aligned} \Delta G_{r,s}^0(298,1) + \Delta G_{f,H_2O}^0(298,1) + \Delta G_{f,CO_2}^0(298,1) - \int_{298}^T e S_{f,r}(T) dT \\ + \int_1^P e \Delta V_{f,r}(P) dP = 0 \end{aligned} \quad 11$$

Expanding $\Delta V_{f,r}$ and $\Delta S_{f,r}$ into separate terms for the solid and fluid phases, as suggested by Fisher and Zen (1971)

$$\begin{aligned} \Delta G_{r,s}^0(298,1) + \Delta G_{f,H_2O}^0(298,1) + \Delta G_{f,CO_2}^0(298,1) - \int_{298}^T e \Delta S_{f,s}(T) dT \\ - \int_{298}^T e \Delta S_{f,H_2O}(T) dT - \int_{298}^T e \Delta S_{f,CO_2}(T) dT + \int_1^P e \Delta V_s(P) dP + \\ \int_1^P e V_{H_2O}(P) dP + \int_1^P e V_{CO_2}(P) dP = 0 \end{aligned} \quad 12$$

The integrals in equation 12 have been evaluated as follows:

$$- \int_{298}^T e S_{f,fl}(T) dT = \Delta G_{f,fl}^0(T_e,1) - \Delta G_{f,fl}^0(298,1) \quad 13$$

$$\int_1^P e V_{H_2O}(P) dP + \int_1^P e V_{CO_2}(P) dP = RT_e \ln K \quad 14$$

$$\int_1^P e \Delta V_s(P) dP = \Delta V_s^0(P_e - 1) \quad 15$$

$$\int_{298}^T e \Delta S_{f,s}(T) dT = \Delta S_{f,s}(T_e - 298) \quad 16$$

Substituting equations 13, 14, 15, and 16 into equation 12

$$\begin{aligned} & \Delta G_{f,s}^0(298,1) - \Delta S_{f,s}^0(T_e - 298) + \Delta G_{f,H_2O}^0(T_e,1) + \Delta G_{f,CO_2}^0(T_e,1) \\ & + \Delta V_s^0(P_e - 1) + RT_e \ln K = 0 \end{aligned} \quad 17$$

Substitution of the relationship

$$\Delta G_{f,s}^0(298,1) = \Delta H_{f,s}^0(298,1) - (298) \left(\Delta S_{f,s}^0(298,1) \right) \quad 18$$

into equation 17 results in equation 19.

$$\begin{aligned} \Delta H_{r,s}^0(298,1) = & -RT_e \ln K + T_e \Delta S_{f,s}^0(298,1) - \Delta V_s^0(P_e - 1) \\ & - \Delta G_{f,H_2O}^0(T_e,1) - \Delta G_{f,CO_2}^0(T_e,1) \end{aligned} \quad 19$$

From Fisher and Zen (1971) the value of $\Delta G_{f,H_2O}^0(t_e,1)$ is

$$\begin{aligned} \Delta G_{f,H_2O}^0(t_e,1) = & -54,742.19408 + 3.748898776t_e - 7.188621229 \times 10^{-5}t_e^2 \\ & + 1.259329484t_e \ln t_e - 2097.329651t_e^{-1} \end{aligned} \quad 20$$

where t_e indicates the temperature in degrees centigrade. The value of $\Delta G_{f,CO_2}^0(T_e,1)$ has been calculated by fitting a curve to the data in Robie and Waldbaum (1968).

$$\begin{aligned} \Delta G_{f,CO_2}^0(T_e,1) = & -93994.26 - 1.018744T_e + .4459984 \times 10^{-3}T_e^2 \\ & - .6190106 \times 10^{-7}T_e^3 \end{aligned} \quad 21$$

The values of $\Delta S_f^0(298,1)$ used to calculate $\Delta S_{f,s}^0(298,1)$ are listed in table III-2. A FORTRAN IV computer program HESTP (see appendix V) has been written to calculate the values of $\Delta H_{r,s}^0(298,1)$ from equations 19, 20 and 21.

$\Delta H_{r,s}^0(298,1)$ for each experimental point was then plotted against the temperature, T_e , at which the experiment was carried out. The results for the reaction

as determined by Chatterjee and Johannes (1974) are shown on figure III-1. Each point on this diagram is calculated from an experimental run, that bracketed the equilibrium temperature. For each point, the experimental uncertainties were added or subtracted in order to achieve the widest bracket on the equilibrium curve. As $\Delta H_{r,s}^0(298,1)$ is a constant, it is independent of the pressure and temperature from which it was calculated. Therefore the points calculated from runs where the products were formed should be above a fixed value of $\Delta H_{r,s}^0(298,1)$ and all points calculated from runs where reactants were formed should be below the fixed value of $\Delta H_{r,s}^0(298,1)$. Thus, these two types of experiments should define an "envelope" or a range of possible values for $\Delta H_{r,s}^0(298,1)$ which should have no dependence on the temperature at which the runs were carried out. This is well illustrated on figure III-1.

Table III-2 Thermodynamic data used in the calculation of
 $\Delta H_{r,s}(298,1)$

Mineral	S^0 $\frac{\text{gibbs}}{\text{gfw.}}$	S^0_f elements $\frac{\text{gibbs}}{\text{gfw.}}$	$V^0 \text{ cm}^3$	Source
Andalusite	22.20	-118.330	51.53	C
Anorthite	48.45	-180.024	100.79	A
Calcite	22.15	- 62.666	36.93	A
Chlorite	106.0	-526.0	211.5	C
Diopside	34.2	-139.548	66.09	A
Grossularite	57.0	-293.866	125.30	A
Kyanite	20.0	-120.53	44.09	C
Muscovite	69.0	-305.474	140.71	A
Phlogopite	76.4	-307.964	149.91	A
Potassic Feldspar	52.46	-178.474	108.72	B
Quartz	9.88	- 43.616	22.69	A
Sanadine	53.38	-177.554	109.05	B
Sillimanite	23.13	-117.40	44.90	C
Tremolite	131.19	-582.920	272.92	A
Zoisite	66.0	-321.2	136.52	C

A Robie & Waldbaum (1968)

B Chatterjee & Johannes (1975)

C Nesbitt (personal communication)

Figure III-1 Standard enthalpy of reaction (25°C , 1 bar) for the solids vs. temperature of experiment for the reaction

Data for the reaction are from Chatterjee and Johannes(1974). The dashed line separates experiments in which reactants formed from experiments in which products formed.

If the values of $\Delta H_{r,s}^0(298,1)$ calculated from the experimental data do show an apparent temperature dependence, then the experiments may not be valid, or the entropies of formation used in equation 19 to calculate $\Delta H_{r,s}^0$ do not correspond to the entropies of formation of the phases actually involved in the reaction. If two laboratories study the same reaction and the results produce two separate envelopes with the same slope, on a plot of $\Delta H_{r,s}^0(298,1)$ vs. T_e , then it is likely that the differences are related to systematic errors in the experimental methods. If the two envelopes have different slopes, then in addition to the possibility of systematic errors, it is possible that the two sets of experiments do not involve identical phases.

Much experimental work has been done in the system, $\text{CaO} - \text{MgO} - \text{Al}_2\text{O}_3 - \text{KAlSi}_3\text{O}_8 - \text{CO}_2 - \text{H}_2\text{O}$, and six reactions have been chosen from available experimental data as follows:

1. $5\text{Ph} + 6\text{Cc} + 24\text{Qz} = 5\text{Kf} + 3\text{Tr} + 6\text{CO}_2 + 2\text{H}_2\text{O}$
2. $\text{Tr} + 3\text{Cc} + 2\text{Qz} = 5\text{Di} + 3\text{CO}_2 + \text{H}_2\text{O}$
3. $\text{Mv} + \text{Qz} = \text{Kf} + \text{Ky} + \text{H}_2\text{O}$
4. $\text{Mv} + \text{Cc} + 2\text{Qz} = \text{Kf} + \text{An} + \text{CO}_2 + \text{H}_2\text{O}$
5. $\text{Mv} + 2\text{Zo} + 2\text{Qz} = \text{Kf} + 4\text{An} + 2\text{H}_2\text{O}$
6. $5\text{Mv} + 3\text{Ch} = 5\text{Ph} + 8\text{Ky} + \text{Qz} + 12\text{H}_2\text{O}$

The internal consistency of experimental data for these six reactions will be discussed in detail in the following sections.

This reaction has been studied by Hoschek (1973) and Hewitt (1975). The $\Delta H_{r,s}^0(298,1)$ vs. T_e diagram for the data is shown on figures III-2 and III-3. It is noted that the slopes obtained from the two sets of experiments are different, suggesting that the phases involved in each study are not identical. Hoschek used synthetic minerals, except for quartz, but Hewitt used natural tremolite seed crystals which contained fluorine. The activity of $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ in the calcic amphibole used by Hewitt was not therefore unity. Also fluorine would be introduced into the vapour phase, diluting the CO_2 and H_2O . For this reason the results given by Hoschek are preferred over the data of Hewitt.

The results on the $\Delta H_{r,s}^0(298,1)$ vs. T_e diagram (figure III-2) suggest that the entropies of formation of the minerals are valid. Therefore the value of B in the gas fugacity product can be calculated from the entropies and this result, along with the experimental data, was used to calculate the value of A. The position of the resulting curve, along with the experimental data, are shown on a $\log K$ vs $1/T$ plot on figure III-4.

Three sources of data for this reaction are available, i.e., Metz (1966), Skippen (1971) and Slaughter et al. (1975). It has been shown (Skippen, personal communication) that the tremolite

used by Metz in his experiments contained appreciable fluorine, and so the results published by Metz cannot be interpreted using a pure, hydroxy-tremolite component. The data of Slaughter et al., when plotted on a $\Delta H_{r,s}^0(298,1)$ vs. T_e plot (see figure III-5), are internally inconsistent and have therefore been rejected. This leaves only the experimental curve calculated by Skippen from the linear combination of three reactions, all of which are internally consistent.

III-3.3 REACTION $Mv + Qz = Kf + Ad + H_2O$

Many researchers have studied this reaction (Evans, 1965; Althaus et al., 1970; Kerrick, 1972; Day, 1973; Chatterjee and Johannes, 1974). However, only Day (1973) and Chatterjee and Johannes (1974) have used well-characterized starting materials.

Plotting the data reported by Chatterjee and Johannes (1974) on a $\Delta H_{r,s}^0(298,1)$ vs. T_e diagram (figure III-1) produces an ideal result. The results of Day (1973) are close to those of Chatterjee and Johannes but fall 15°C to 20°C higher at a given pressure.

Hovis (1974) has demonstrated that the enthalpy, volume and entropy of sanidine are functions of the actual tetrahedral site population of Al and Si in the monoclinic, potassic feldspar. The arrangement of Al and Si on tetrahedral sites can conveniently be expressed in terms of the long range ordering parameter, Z , which can be calculated from the b and c cell dimensions according to the formula: (Hovis, 1974)

$$Z = 7.6344 - 4.3584b + 6.8615c$$

Chatterjee and Johannes (1974) have determined the cell dimensions of the feldspars in their experiments and these data are used to calculate the degree of order in the feldspar. From this and the work of Hovis (1974) the thermochemical parameters for the actual feldspar which was involved in the experiment can be calculated. As the value of Z does not have any regular relationship with the temperature of the experiments by Chatterjee and Johannes, the average value, 0.1607, has been calculated and used for all runs. The corresponding value of $S^0(298,1)$ for the potassic feldspar was 53.26. This value was used to calculate $\Delta H_{r,s}^0(298,1)$ for the reaction. Day (1973) does not give any information on the cell parameters of feldspars, so it is not certain whether his feldspars were ordered to the same extent as those of Chatterjee and Johannes (1974). Day also states that he had difficulty in identifying the reverse reaction, so his results should be interpreted as providing only maximum temperatures for the equilibrium curve.

For the above reasons, and because the data of Chatterjee and Johannes (1974) more tightly constrain the reaction, the equilibrium constants calculated from the data of Chatterjee and Johannes are used subsequently.

As the results on the $\Delta H_{r,s}^0(298,1)$ vs. T_e diagram are ideal, the B value of the gas fugacity product is calculated from the standard entropy of reaction. This value was used in plotting a curve through the experimental points as for reaction 3 and the resultant curve is shown on figure III-6.

III-3.4 REACTION $Mv + Cc + 2Qz \rightleftharpoons Kf + An + CO_2 + H_2O$

The above reaction was studied by Hewitt (1973a). The $\Delta H_{r,s}^0(298,1)$ vs. T_e , and $\log K$ vs. $1/T$ plots for this reaction are shown on figures III-7 and III-8. From the $\Delta H_{r,s}^0(298,1)$ vs. T_e diagram it is observed that an envelope with zero slope has been obtained. This along with a consistent linear relationship on the $\log K$ vs. $1/T$ diagram suggests that this experimental work is internally consistent. The value B of the gas fugacity product has been calculated from the entropy of reaction, and the value of A has been calculated from the experimental data and B.

III-3.5 REACTION $Mv + 2Zo + 2Qz = Kf + 4An + 2H_2O$

Data for this reaction have been taken from Ackerman and Karl (1972) who studied the three reactions:

The intersection of reactions (a) and (b) can be used as another point to restrict the position of reaction (c), since reaction (c) is implicit in the intersection of reactions (a) and (b).

Two of the three reactions have a fairly steep slope on the $\Delta H_{r,s}^0(298,1)$ vs. T_e plot (figures III-9, III-10, and III-11),

but the thermochemical data for zoisite and grossularite, used in the calculation of $\Delta H_{r,s}^0(298,1)$ are not well known. The slopes on the $\Delta H_{r,s}^0(298,1)$ vs. T_e plots are interpreted to be due to uncertainties in the thermochemical data rather than poor experimental technique. The three reactions intersect on a $\log K$ vs. $1/T$ diagram (figure III-12) and show consistent linear relationships. The value of B was not calculated from the entropy of reaction as the $\Delta H_{r,s}^0(298,1)$ vs. T_e plots show the unreliability of the entropy data.

III-3.6 REACTION $5Mv + 3Ch = 5Ph + 8Ky + Qz + 12H_2O$

This reaction was studied by Bird and Fawcett (1973), but the two available reversals are too close together to permit extrapolation (figures III-13 and III-14). However, as entropies for the phases are available, the value of B in the gas fugacity product can be readily calculated. Using this predetermined value of B the curve shown on figure III-14 was fitted through the experimental brackets.

III-3.7 THE ALUMINOSILICATE MINERALS

Much work has been done on the aluminosilicate problem with no definitive answers yet available. The aluminosilicate phase relations given by Holdaway (1971) have been used in this work.

An adjustment in the gas fugacity products of a reaction

for different aluminosilicate polymorphs was made by assuming reactions of the type:

a) andalusite = kyanite

b) andalusite = sillimanite

The values of A, B, and C for the above reactions were calculated from equations 6, 7, and 8. The values of ΔH_r and ΔS_r for equations 6 and 7 were calculated from the following equations:

$$\Delta H_r(T_e, 1) = \Delta H_r^0(298, 1) + \int_{298}^{T_e} \Delta C_p dT \quad 22$$

$$\Delta S_r(T_e, 1) = \Delta S_r^0(298, 1) + \int_{298}^{T_e} \frac{\Delta C_p}{T} dT \quad 23$$

The values of ΔH_r and ΔS_r for both aluminosilicate reactions change only a small amount above 400°C so the average values of ΔH_r and ΔS_r from 400°C to 900°C were used in equations 6 and 7 to adjust the gas fugacity products of other reactions. The enthalpy, entropy, molar volume and heat capacity data are listed in table III-3. The heat capacity data are calculated from the JANAF Tables (1971) (Nesbitt, personal communication) and the entropies have been made consistent with the experimental data of Holdaway (1971). The adjustments for the various aluminosilicate minerals have been included in the data for the six independent equilibria given in table III-4.

Figure III-2 Standard enthalpy of reaction(25°C,1bar) for the solids vs. temperature of experiment for the reaction

Experimental data are from Hoschek(1973). The dashed line separates experiments in which reactants formed from experiments in which products formed.

Figure III-3 Standard enthalpy of reaction(25°C, 1 bar) for the solids vs. temperature of experiment for the reaction

$$5\text{Ph} + 6\text{Cc} + 24\text{Qz} = 5\text{Kf} + 3\text{Tr} + 6\text{CO}_2 + \text{H}_2\text{O}$$

Experimental data are from Hewitt(1975). The dashed line separates experiments in which reactants formed from experiments in which products formed.

Figure III-4 Log K vs. reciprocal temperature ($^{\circ}\text{K}$) for the reaction

Experimental data are from Hosc hek (1973) and the values of log K are converted to a standard pressure of 2000 bars.

Figure III-5 Standard enthalpy of reaction(25°C,1bar) for the solids vs. temperature of experiment for the reaction

Experimental data are from Slaughter et. al.(1975).

Figure III-6 Log K vs. reciprocal temperature ($^{\circ}\text{K}$) for the reaction

Experimental data are from Chatterjee and Johannes (1974) and the values of log K are converted to a standard pressure of 2000 bars.

Figure III-7 Standard enthalpy of reaction(25°C,1bar) for the solids vs. temperature of experiment for the reaction

Experimental data are from Hewitt(1974). The dashed line separates experiments in which reactants formed from experiments in which products formed.

Figure III-8 Log K vs. reciprocal temperature ($^{\circ}\text{K}$) for the reaction

Experimental data are from Hewitt(1974) and the values of log K are converted to a standard pressure of 2000 bars.

Figure III-9 Standard enthalpy of reaction(25°C,1bar) for the solids vs. temperature of experiment for the reaction

$$2Mv + Gr + 3Qz = 2Kf + 3An + 2H_2O$$

Experimental data are from Ackemand and Karl(1972). The dashed line separates experiments in which reactants formed from experiments in which products formed.

Figure III-10 Standard enthalpy of reaction(25°C, 1bar) for the solids vs. temperature of experiment for the reaction

Experimental data are from Ackermann and Karl(1972). The dashed line separates experiments in which reactants formed from experiments in which products formed.

Figure III-11 Standard enthalpy of reaction (25°C, 1 bar) for the solids vs. temperature of experiment for the reaction

Experimental data are from Ackerman and Karl (1972). The dashed line separates experiments in which reactants formed from experiments in which products formed.

Figure III-12 Log K vs reciprocal temperature ($^{\circ}\text{K}$) for the reactions

Experimental data are from Ackerman and Karl (1972) and the values of log K are converted to a standard pressure of 2000 bars.

Figure III-13 Standard enthalpy of reaction (25°C, 1 bar) for the solids vs. temperature of experiment for the reaction

Experimental data are from Bird and Fawcett (1973). The dashed line separates experiments in which reactants are formed from experiments in which products are formed.

Figure III-14 Log K vs. reciprocal temperature ($^{\circ}\text{K}$) for the reaction

Experimental data are from Bird and Fawcett (1973) and the values of log K are converted to a standard pressure of 2000 bars.

Table III-3 Thermodynamic Properties of the Aluminosilicate Polymorphs.

Cp Power Functions

	H_f^0 cal	S^0	V^0 cm ³	A	B	C
Ky	-614940.	20.0	44.09	41.393	6.8165×10^{-3}	-12.882×10^5
Ad	-613910.	22.20	51.53	41.311	6.293×10^{-3}	-12.392×10^5
Sl	-613145.	23.13	49.90	40.024	7.391×10^{-3}	-11.674×10^5

The heat capacities are expressed in terms of the Maier-Kelly

Heat Capacity Coefficients, i.e.,

$$C_p \approx A + BT + CT^{-2}$$

Table III-4 Gas Fugacity Products for 6 Independent Equilibria

	A	B	C
$5\text{Ph} + 6\text{Cc} + 24\text{Qz} = 5\text{Kf} + 3\text{Tr} + 6\text{CO}_2 + 2\text{H}_2\text{O}$	-31,362.	64.92	0.8004
$\text{Tr} + 3\text{Cc} + 2\text{Qz} = 5\text{Di} + 3\text{CO}_2 + \text{H}_2\text{O}$	-12,486.	27.95	0.5152
$\text{Mv} + \text{Qz} = \text{Kf} + \text{Ky} + \text{H}_2\text{O}$	- 4,194.	-7.692	0.0553
$\text{Mv} + \text{Cc} + 2\text{Qz} = \text{Kf} + \text{An} + \text{CO}_2 + \text{H}_2\text{O}$	-10,029.	19.09	0.0705
$\text{Mv} + 2\text{Zo} + 2\text{Qz} = \text{Kf} + 4\text{An} + 2\text{H}_2\text{O}$	- 8,988.	18.74	-0.2754
$5\text{Mv} + 3\text{Ch} = 5\text{Ph} + 8\text{Ky} + \text{Qz} + 12\text{H}_2\text{O}$	-49,909.	93.97	1.1123
$5\text{Mv} + 3\text{Ch} = 5\text{Ph} + 8\text{Ad} + \text{Qz} + 12\text{H}_2\text{O}$	-52,061.	97.47	0.8011
$5\text{Mv} + 3\text{Ch} = 5\text{Ph} + 8\text{St} + \text{Qz} + 12\text{H}_2\text{O}$	-52,877.	98.39	0.8685
$\text{Mv} + \text{Qz} = \text{Kf} + \text{Ad} + \text{H}_2\text{O}$	- 4,463.	8.130	0.0164
$\text{Mv} + \text{Qz} = \text{Kf} + \text{St} + \text{H}_2\text{O}$	- 4,565.	8.245	0.0250

III-4 REACTION EQUILIBRIA

The relationships of the 68 dependent reactions to the 6 independent reactions were computed with the computer program KCON (see appendix VI) and are written in the form:

$$\log K_N = k_1 \log K_1 + k_2 \log K_2 + k_3 \log K_3 \dots k_n \log K_n \quad 24$$

These constants (table III-5) were used in conjunction with the equilibrium constants of the independent reactions to produce the equilibrium constants for the 68 dependent reactions. This was done with the computer program RECALC (appendix VII) and the results are shown on table III-6.

III-5 LOG-FUGACITY DIAGRAMS

Log-fugacity diagrams are readily derived from equation 5 e.g., Skippen (1975), and provide considerable insight into the relationships between fluid composition and stability of solid phases. The logarithm of the fugacity is directly related to the chemical potential, and, log-fugacity diagrams are therefore similar to the chemical potential diagrams used by Korzhinskii (1959) to represent mixed-volatile equilibria.

From equation 5, $\log K$ can be calculated for any P , and T of reaction. Then from equation 3, the $\log$ fugacity of CO_2 can be expressed as a function of $\log$ fugacity of H_2O for any desired reaction at specified values of pressure and temperature. In this way reactions are located on the $\log$ fugacity diagrams with the

Table III-5 Dependence of reactions on the 6 independent reactions

k_1	k_2	k_3	k_4	k_5	k_6
1.000	1.000	.000	.000	.000	-.000
2.000	-.000	2.000	.000	.000	-.000
3.000	.000	.000	1.000	.000	.000
4.000	.000	.000	.000	1.000	.000
5.000	.000	.000	.000	.000	1.000
6.000	.000	-.000	.000	.000	1.000
7.000	3.000	-20.000	-24.000	12.000	-3.000
8.000	.333	-1.000	-2.667	1.000	.000
9.000	1.000	-2.000	-5.000	.000	1.000
10.000	.333	1.000	-2.667	-5.000	.000
11.000	1.333	4.000	8.333	-20.000	5.000
12.000	.333	.000	-2.667	-2.000	3.000
13.000	.667	-.000	-.333	-4.000	1.000
14.000	.333	1.000	3.333	-5.000	.000
15.000	.333	-.000	.333	-2.000	.000
16.000	1.000	3.000	-8.000	4.000	-1.000
17.000	.333	1.000	-2.667	1.000	.000
18.000	.333	1.000	-1.667	.000	.000
19.000	1.000	.000	-8.000	4.000	-1.000
20.000	.333	.000	-2.667	1.000	.000
21.000	.333	.000	-1.667	.000	.000
22.000	.000	4.000	9.000	-12.000	3.000
23.000	.000	1.000	.000	-3.000	3.000
24.000	-.000	1.000	3.000	-3.000	.000
25.000	.000	.000	-1.000	.000	1.000
26.000	-.000	.000	-.000	1.000	-1.000
27.000	-.000	.000	-3.000	4.000	-1.000
28.000	.000	.000	-1.000	1.000	.000
29.000	1.600	-3.200	-8.000	.000	.000
30.000	.533	1.600	-2.667	.000	.000
31.000	2.667	.000	-13.333	.000	.000
32.000	.200	.600	.000	-3.000	3.000
33.000	.800	2.400	9.000	-12.000	3.000
34.000	1.200	.000	.000	-6.000	6.000
35.000	2.000	.000	9.000	-12.000	3.000
36.000	.200	.600	.000	-3.000	2.000
37.000	.600	1.200	.000	-4.000	1.000
38.000	.200	.600	3.000	-3.000	.000
39.000	1.000	.000	6.000	-6.000	.000
40.000	.200	.600	-.000	-1.000	.000
41.000	1.000	-.000	-.000	-5.000	.000
42.000	.200	.600	-1.000	.000	.000
43.000	1.000	.000	-5.000	.000	.000
44.000	.200	.600	.000	.000	.000
45.000	.000	-.000	-8.000	.000	1.000
46.000	-.800	-2.400	-24.000	12.000	-3.000
47.000	-.067	-.200	-2.667	1.000	.000
48.000	-2.000	-.000	-24.000	12.000	-3.000
49.000	-.333	-.000	-5.333	2.000	.000
50.000	.000	-.000	-8.000	.000	3.000
51.000	-.000	-.000	-8.000	4.000	-1.000
52.000	.000	-.000	-8.000	3.000	.000
53.000	-.200	2.400	.000	.000	.000
54.000	.000	-.000	-5.000	.000	.000
55.000	-2.133	-6.400	-13.333	32.000	-8.000
56.000	-.267	-.800	-2.667	4.000	.000
57.000	-2.667	-.000	-2.667	16.000	.000
58.000	.000	.000	-8.000	.000	8.000
59.000	-.000	.000	-24.000	32.000	-8.000
60.000	.000	.000	-8.000	8.000	.000
61.000	-2.000	-.000	-.000	12.000	-3.000
62.000	-.800	-2.400	-.000	12.000	-3.000
63.000	-.200	-.600	.000	3.000	.000
64.000	-1.000	.000	.000	6.000	.000
65.000	-5.333	-.000	2.667	32.000	-8.000
66.000	-.200	.600	1.000	.000	.000
67.000	-1.000	.000	.000	6.000	-1.000
68.000	-2.000	.000	1.000	12.000	-3.000
69.000	-1.200	-.400	-.000	12.000	-3.000
70.000	-1.000	.000	-1.000	6.000	.000
71.000	-3.000	-.000	-.000	20.000	-5.000
72.000	-.000	.000	-.000	4.000	-1.000
73.000	.000	2.400	5.000	-12.000	3.000
74.000	-.600	.200	.000	3.000	.000

Table III-6 Equilibrium data for independent and dependent reactions.

Reaction	A	B	C	$\frac{\text{CO}_2}{\text{Mole}}$	$\frac{\text{H}_2\text{O}}{\text{Mole}}$
1: $5\text{PH}+6\text{CC}+24\text{QZ}=5\text{KF}+3\text{TR}+6\text{CD}+2\text{WA}$	-31362.	64.920	.8004	6.0	2.0
2: $\text{TR}+3\text{CC}+2\text{QZ}=5\text{DI}+3\text{CD}+\text{WA}$	-12486.	27.950	.5152	3.0	1.0
3: $\text{MV}+\text{QZ}=\text{KF}+\text{KY}+\text{WA}$	-4194.	7.692	.0553	.0	1.0
3: $\text{MV}+\text{OZ}=\text{KF}+\text{SL}+\text{WA}$	-4565.	8.245	.0250	.0	1.0
3: $\text{MV}+\text{QZ}=\text{KF}+\text{AD}+\text{WA}$	-4463.	8.130	.0164	.0	1.0
4: $\text{MV}+\text{CC}+2\text{QZ}=\text{KF}+\text{AN}+\text{CD}+\text{WA}$	-10029.	19.090	.0705	1.0	1.0
5: $\text{MV}+2\text{ZO}+2\text{QZ}=\text{KF}+4\text{AN}+2\text{WA}$	-8988.	18.740	-.2754	.0	2.0
6: $5\text{MV}+3\text{CH}=5\text{PH}+8\text{KY}+\text{QZ}+12\text{WA}$	-49909.	93.970	1.1123	.0	12.0
6: $5\text{MV}+3\text{CH}=5\text{PH}+8\text{SL}+\text{QZ}+12\text{WA}$	-52877.	98.390	.8685	.0	12.0
6: $5\text{MV}+3\text{CH}=5\text{PH}+8\text{AD}+\text{QZ}+12\text{WA}$	-52061.	97.470	.8011	.0	12.0
7: $9\text{CH}+50\text{DI}+43\text{QZ}=19\text{TR}+62\text{O}+14\text{WA}$	-111681.	185.410	.9311	.0	14.0
8: $\text{CH}+5\text{DI}+5\text{QZ}=2\text{TR}+\text{AN}+2\text{WA}$	-13420.	23.533	.0449	.0	2.0
9: $3\text{CH}+10\text{DI}+14\text{QZ}=5\text{TR}+3\text{KY}+7\text{WA}$	-35329.	64.530	.6058	.0	7.0
9: $3\text{CH}+10\text{DI}+14\text{QZ}=5\text{TR}+3\text{SL}+7\text{WA}$	-36442.	66.185	.5135	.0	7.0
9: $3\text{CH}+10\text{DI}+14\text{QZ}=5\text{TR}+3\text{AD}+7\text{WA}$	-36136.	65.840	.4891	.0	7.0
10: $\text{CH}+12\text{ZO}+9\text{QZ}=19\text{AN}+10\text{WA}$	-32146.	77.333	-1.0001	.0	10.0
11: $4\text{CH}+10\text{ZO}+17\text{QZ}=20\text{DI}+19\text{KY}+21\text{WA}$	-37587.	99.598	2.2842	.0	21.0
11: $4\text{CH}+10\text{ZO}+17\text{QZ}=20\text{DI}+19\text{SL}+21\text{WA}$	-44635.	110.098	1.7068	.0	21.0
11: $4\text{CH}+10\text{ZO}+17\text{QZ}=20\text{DI}+19\text{AD}+21\text{WA}$	-42697.	107.913	1.5453	.0	21.0
12: $\text{CH}+6\text{ZO}+7\text{QZ}=\text{TR}+10\text{AN}+6\text{WA}$	-22783.	50.433	-.4781	.0	6.0
13: $2\text{CH}+2\text{ZO}+9\text{QZ}=2\text{TR}+5\text{KY}+7\text{WA}$	-21683.	45.798	.7000	.0	7.0
13: $2\text{CH}+2\text{ZO}+9\text{QZ}=2\text{TR}+5\text{SL}+7\text{WA}$	-23539.	48.562	.5474	.0	7.0
13: $2\text{CH}+2\text{ZO}+9\text{QZ}=2\text{TR}+5\text{AD}+7\text{WA}$	-23029.	47.987	.5053	.0	7.0
14: $\text{CH}+5\text{AN}+3\text{QZ}=5\text{DI}+6\text{KY}+4\text{WA}$	-3383.	11.048	.9839	.0	4.0
14: $\text{CH}+5\text{AN}+3\text{QZ}=5\text{DI}+6\text{SL}+4\text{WA}$	-5608.	14.363	.8018	.0	4.0
14: $\text{CH}+5\text{AN}+3\text{QZ}=5\text{DI}+6\text{AD}+4\text{WA}$	-4996.	13.673	.7507	.0	4.0
15: $\text{CH}+2\text{AN}+4\text{OZ}=\text{TR}+3\text{KY}+3\text{WA}$	-8402.	17.292	.5143	.0	3.0

15:	CH+2AN+4QZ=TR+3SL+3WA	-9514.	18.948	.4231	.0	3.0
15:	CH+2AN+4QZ=TR+3AD+3WA	-9208.	18.603	.3978	.0	3.0
16:	3CH+19CC+27QZ=15DI+2ZO+19CD+11WA	-116305.	238.820	3.5733	19.0	11.0
17:	CH+6CC+9QZ=5DI+AN+6CD+4WA	-38392.	79.433	1.0753	6.0	4.0
18:	CH+5CC+8QZ=5DI+KY+5CD+4WA	-32558.	68.038	1.0599	5.0	4.0
18:	CH+5CC+8QZ=5DI+SL+5CD+4WA	-32928.	68.588	1.0293	5.0	4.0
18:	CH+5CC+8QZ=5DI+AD+5CD+4WA	-32826.	68.473	1.0212	5.0	4.0
19:	3CH+10CC+21QZ=3TR+2ZO+10CD+8WA	-39424.	77.485	1.0132	5.0	4.0
20:	CH+3CC+7QZ=TR+AN+3CD+3WA	-25906.	51.483	.5601	3.0	3.0
21:	CH+2CC+6QZ=TR+KY+2CD+3WA	-20072.	40.088	.5447	2.0	3.0
21:	CH+2CC+6QZ=TR+SL+2CD+3WA	-20442.	40.638	.5141	2.0	3.0
21:	CH+2CC+6QZ=TR+AD+2CD+3WA	-20340.	40.523	.5060	2.0	3.0
22:	4TR+6ZO=20DI+9KY+QZ+7WA	5694.	8.168	.8863	.0	7.0
22:	4TR+6ZO=20DI+9SL+QZ+7WA	2355.	13.145	.6136	.0	7.0
22:	4TR+6ZO=20DI+9AD+QZ+7WA	3273.	12.110	.5362	.0	7.0
23:	TR+6ZO+2QZ=5DI+9AN+4WA	-9363.	26.900	-.5225	.0	4.0
24:	TR+3AN=5DI+3KY+QZ+WA	5019.	-6.244	.4696	.0	1.0
24:	TR+3AN=5DI+3SL+QZ+WA	3906.	-4.585	.3787	.0	1.0
24:	TR+3AN=5DI+3AD+QZ+WA	4212.	-4.930	.3529	.0	1.0
25:	2ZO+KY+QZ=4AN+WA	-4794.	11.048	-.3307	.0	1.0
25:	2ZO+SL+QZ=4AN+WA	-4423.	10.495	-.3004	.0	1.0
25:	2ZO+AD+QZ=4AN+WA	-4525.	10.610	-.2918	.0	1.0
26:	3AN+CC+WA=2ZO+CD	-1041.	.350	.3459	1.0	-1.0
27:	3KY+4CC+3QZ+WA=2ZO+4CD	-18546.	34.544	.3915	4.0	-1.0
27:	3SL+4CC+3QZ+WA=2ZO+4CD	-17433.	32.885	.4824	4.0	-1.0
27:	3AD+4CC+3QZ+WA=2ZO+4CD	-17739.	33.230	.5082	4.0	-1.0
28:	KY+CC+QZ=AN+CD	-5835.	11.398	.0152	1.0	.0
28:	SL+CC+QZ=AN+CD	-5464.	10.845	.0455	1.0	.0
28:	AD+CC+QZ=AN+CD	-5506.	10.960	.0541	1.0	.0
29:	3PH+3CH+16DI+23QZ=3MV+8TR+4WA	-26581.	46.802	.3019	.0	4.0
30:	PH+CH+13QZ=3MV+8DI+8CD+4WA	-42127.	90.097	1.4740	8.0	4.0
31:	5PH+5CH+16CC+49QZ=5M+8TC+16CD+12WA	-27731.	56.807	.8123	4.	3.
32:	PH+6ZO+6QZ=KF+3DI+9AN+4WA	-10641.	28.704	-.5685	.0	4.0

33:	4PH+6ZO+15QZ=4KF+12DI+9KY+7WA	582.	15.384	.7023	.0	7.0
33:	4PH+6ZO+15QZ=4KF+12DI+9SL+7WA	-2757.	20.361	.4296	.0	7.0
33:	4PH+6ZO+15QZ=4KF+12DI+9AD+7WA	-1839.	19.326	.3522	.0	7.0
34:	5PH+12ZO+24QZ=5KF+3TR+18AN+8WA	-25116.	62.820	-1.2750	.0	8.0
35:	10PH+6ZO+39QZ=10KF+6TR+9KY+7WA	-7086.	26.208	.4263	.0	7.0
35:	10PH+6ZO+39QZ=10KF+6TR+9SL+7WA	-10425.	31.185	.1536	.0	7.0
35:	10PH+6ZO+39QZ=10KF+6TR+9AD+7WA	-9507.	30.150	.0762	.0	7.0
36:	PH+4ZO+4OZ=MV+3DI+5AN+2WA	-1653.	9.964	-.2931	.0	2.0
37:	3PH+2ZO+5CC+12QZ=3MV+9DI+5CD+WA	-10164.	31.642	.8502	5.0	1.0
38:	PH+3AN+3QZ=KF+3DI+3KY+WA	3741.	-4.440	.4236	.0	1.0
38:	PH+3AN+3QZ=KF+3DI+3SL+WA	2628.	-2.781	.3327	.0	1.0
38:	PH+3AN+3QZ=KF+3DI+3AD+WA	2934.	-3.126	.3069	.0	1.0
39:	5PH+6AN+18QZ=5KF+3TR+6KY+2WA	-3648.	3.468	-.7092	.0	-2.0
39:	5PH+6AN+18QZ=5KF+3TR+6SL+2WA	-1422.	.150	-.5274	.0	-2.0
39:	5PH+6AN+18QZ=5KF+3TR+6AD+2WA	-2034.	.840	-.4758	.0	-2.0
40:	PH+AN+2CC+4QZ=MV+3DI+2CD	-3735.	10.664	.3987	2.0	.0
41:	5PH+5AN+CC+14QZ+3VA=5MV+3TR+CD	18783.	-30.530	.4479	1.0	-3.0
42:	PH+KY+3CC+5QZ=MV+3DI+3CD	-9570.	22.062	.4139	3.0	.0
42:	PH+SL+3CC+5QZ=MV+3DI+3CD	-9199.	21.509	.4442	3.0	.0
42:	PH+AD+3CC+5QZ=MV+3DI+3CD	-9301.	21.624	.4528	3.0	.0
43:	5PH+5KY+6CC+19QZ+3WA=5MV+3TR+6CD	-10392.	26.460	.5239	6.0	-3.0
43:	5PH+5SL+6CC+19QZ+3WA=5MV+3TR+6CD	-8537.	23.695	.6754	6.0	-3.0
43:	5PH+5AD+6CC+19QZ+3WA=5MV+3TR+6CD	-9047.	24.270	.7184	6.0	-3.0
44:	PH+3CC+6QZ=KF+3DI+3CD+WA	-13764.	29.754	.4692	3.0	1.0
45:	8KF+3CH=5PH+3MV+9QZ+4WA	-16357.	32.430	.6699	.0	4.0
46:	19KF+9CH+12DI=19PH+6ZO+33OZ+14WA	-87399.	151.134	1.8051	.0	14.0
47:	2KF+CH+DI=2PH+AN+3OZ+2WA	-10864.	19.925	.1369	.0	2.0
48:	25KF+9CH+6TR=25PH+6ZO+57QZ+14WA	-79731.	140.310	2.0811	.0	14.0
49:	5KF+2CH+TR=5PH+2AN+10QZ+4WA	-20538.	38.217	.3213	.0	4.0
50:	5KF+3CH+6ZO=5PH+12AN+3OZ+10WA	-43321.	88.650	-.1563	.0	10.0
51:	5KF+3CH+4CC=5PH+2ZO+3OZ+4CD+6WA	-47485.	90.050	1.2273	4.0	6.0
52:	5KF+3CH+3CC=5PH+3AN+3OZ+3CD+7WA	-46444.	89.700	.8814	3.0	7.0
53:	KF+3TR+6CC=PH+12DI+6CD+2WA	-23694.	54.096	1.0764	6.0	2.0

54: 5KF+3CH=5PH+3KY+6QZ+7WA	-28939.	55.510	.8358	.0	7.0
54: 5KF+3CH=5PH+3SL+6QZ+7WA	-30052.	57.165	.7435	.0	7.0
54: 5KF+3CH=5PH+3AD+6QZ+7WA	-29746.	56.820	.7191	.0	7.0
55: 19MV+5CH+32DI=19PH+19ZO+31QZ+12WA	-129499.	197.691	.5714	.0	12.0
56: 3MV+CH+4DI=3PH+4AN+3QZ+4WA	-27187.	47.441	-.1208	.0	4.0
57: 15MV+CH+8TR=15PH+16AN+35QZ+12WA	-41128.	71.536	-.3921	.0	6.
58: 5MV+3CH+16ZO+7QZ=5PH+32AN+20WA	-8825.	18.235	-.1535	.0	2.
59: 15M+9CH+32CC+21Q=15P+16Z+32CD+28WA	-74524.	139.562	1.6172	8.	7.
60: 5MV+3CH+8CC+7QZ=5PH+8AN+8CD+12WA	-24147.	46.287	.3085	2.	3.0
61: 9MV+KF+6TR=10PH+6ZO+30QZ+2WA	-30660.	43.020	.0714	.0	2.0
62: 9MV+12DI=4PH+5KF+6ZO+6QZ+2WA	-38328.	53.844	-.2046	.0	2.0
63: 3MV+3DI=PH+2KF+3AN+2WA	-16323.	27.516	-.2577	.0	2.0
64: 6MV+3TR=5PH+KF+6AN+12QZ+4WA	-28812.	49.620	-.3774	.0	4.0
65: 25MV+16TR=25PH+CH+16ZO+77QZ+4WA	-76337.	103.967	-.0319	.0	4.0
66: NV+TR=PH+2DI+KY+3QZ+WA	-2916.	5.888	.1013	.0	1.0
66: NV+TR=PH+2DI+SL+3QZ+WA	-3287.	6.441	.0710	.0	1.0
66: NV+TR=PH+2DI+AD+3QZ+WA	-3185.	6.326	.0624	.0	1.0
67: 5MV+3TR=PH+2ZO+2AN+14QZ+2WA	-19824.	30.880	-.1020	.0	2.0
68: 10MV+6TR=10PH+6ZO+KY+29QZ+3WA	-34854.	50.712	.1267	.0	3.0
68: 10MV+6TR=10PH+6ZO+SL+29QZ+3WA	-35225.	51.265	.0964	.0	3.0
68: 10MV+6TR=10PH+6ZO+AD+29QZ+3WA	-35123.	51.150	.0878	.0	3.0
69: 9MV+5TR+2DI=9PH+6ZO+26QZ+2WA	-31938.	44.824	.0254	.0	2.0
70: 5MV+3TR+KY=5PH+6AN+13QZ+3WA	-24618.	41.928	-.4327	.0	3.0
70: 5MV+3TR+SL=5PH+6AN+13QZ+3WA	-24247.	41.375	-.4024	.0	3.0
70: 5MV+3TR+AD=5PH+6AN+13QZ+3WA	-24349.	41.490	-.3938	.0	3.0
71: 15M+9TR+2CC=15PH+10Z+42Q+2CD+4WA	-61554.	93.340	.3858	2.0	4.0
72: 3MV+4CC+6QZ=3KF+2ZO+4CD+2WA	-51128.	57.620	.5574	4.0	2.0
73: 4PH+6ZO+11QZ=4MV+12DI+5KY+3WA	17358.	-15.384	.4811	.0	3.0
73: 4PH+6ZO+11QZ=4MV+12DI+5SL+3WA	15503.	-12.619	.3296	.0	3.0
73: 4PH+6ZO+11QZ=4MV+12DI+5AD+3WA	16013.	-13.194	.2866	.0	3.0
74: 3MV+2TR=3PH+DI+3AN+8QZ+2WA	-13767.	23.908	-.1657	.0	2.0

relative stabilities around invariant points determined using Schreinmakers rules (Zen, 1966; Skippen, 1974) in conjunction with the K.A.L. projection.

The relative stabilities of invariant points to one another were determined by the method of Korzhinskii (1959). As there was only one carbonate phase considered in this model, all invariant points must contain at least one dehydration reaction. If these dehydration reactions are plotted on a $\log f_{\text{CO}_2}$ vs. $\log f_{\text{H}_2\text{O}}$ diagram, then by inspection, many of the dehydration reactions can be shown to be metastable. For example, on figure III-15, no stable dehydration reaction can involve muscovite at lower H_2O fugacities than indicated for reaction 3 (i.e., the muscovite breakdown reaction). Similarly, any reactions containing muscovite above reaction 45 would be metastable since reaction 45 requires the breakdown of muscovite in the presence of biotite, quartz, and H_2O (i.e., minerals implicit in the K.A.L. projection) to form potassic feldspar and chlorite. Thus, by eliminating the invariant points which contain metastable dehydration reactions, the graphical analysis derived by Korzhinskii (1959) can be considerably shortened.

Log fugacity diagrams have been calculated for pressures of 2, 6 and 10 kilobars at temperatures of 400°C , 600°C and 800°C . The results are shown on figures III-16 through III-24.

Many changes can be seen on these diagrams from one set of conditions to another. Two important observations to note are that diopside is absent at 600°C and above at 2 and 6 kilobars, and at 800°C and above at 10 Kbars. Zoisite is not stable at 2 kilobars. This would suggest that pure zoisite would not be stable during low

↑ log $f_{\text{H}_2\text{O}}$

→ log f_{CO_2}

Figure III-15 Schematic log $f_{\text{H}_2\text{O}}$ vs. log f_{CO_2} for dehydration reactions.

Figure III-16 Log fugacity H_2O vs. log fugacity CO_2 at 2000 bars and $400^\circ C$ showing relationships among stable, invariant assemblages. Numbers in circles refer to the invariant assemblages

- (1) Ph-Qz-Kf-Di-Cc-An-Ad
- (20) Ph-Qz-Mv-Di-Tr-Cc-An
- (21) Ph-Qz-Mv-Ch-Cc-An-Ad
- (27) Ph-Qz-Mv-Ch-Tr-Cc-An
- (30) Ph-Qz-Mv-Ch-Tr-Di-Cc
- (31) Qz-Kf-Mv-Cc-An-Ad
- (34) Ph-Qz-Kf-Mv-Di-Cc-An
- (46) Ph-Qz-Kf-Mv-Ch-Di-Cc
- (52) Qz-Ch-Tr-An-Cc-Ad
- (119) Qz-Tr-Di-Cc-An-Ad

Numbered lines refer to equilibria listed in table III-6. Stable divariant assemblages are illustrated on the KAL projection. The P_{total} surface is at higher values of $\log f_{H_2O}$ and $\log f_{CO_2}$ than are plotted on this diagram.

Figure III-17 Log fugacity H_2O vs. log fugacity CO_2 at 2000 bars and $600^\circ C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages

- (2) Ph-Qz-Kf-Tr-Cc-An-Ad
- (12) Ph-Qz-Kf-Ch-Tr-Cc-An
- (21) Ph-Qz-Mv-Ch-Cc-An-Ad
- (31) Qz-Mv-Kf-Cc-An-Ad
- (48) Ph-Qz-Mv-Kf-Ch-Tr-An
- (52) Qz-Ch-Tr-Cc-An-Ad

Numbered lines refer to equilibria listed in table III-6. Stable divariant assemblages are illustrated on the KAL projection. The dotted line is the P_{total} surface.

Figure III-18. Log fugacity H_2O vs log fugacity CO_2 at 2000 bars and $800^\circ C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Sl
- (12) Ph-Qz-Kf-Ch-Tr-Cc-An
- (21) Ph-Qz-Mv-Ch-Cc-An-Sl
- (31) Qz-Mv-Kf-Cc-An-Sl
- (48) Ph-Qz-Mv-Kf-Ch-Tr-An
- (52) Qz-Ch-Tr-An-Cc-Sl

Numbered lines refer to equilibria listed in table III-6. Stable divariant assemblages are illustrated on the KAL projection. The P_{total} surface is at lower values of log f_{H_2O} and log f_{CO_2} than are plotted on this diagram.

Figure III-19 Log fugacity H_2O vs. log fugacity CO_2 at 6000 bars and $400^\circ C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages

(19) Ph-Qz-Mv-Di-Tr-Cc-An

(26) Ph-Qz-Mv-Ch-Tr-An-Ky

(30) Ph-Qz-Mv-Ch-Tr-Di-Cc

(33) Ph-Qz-Kf-Mv-Di-Cc-Ky

(46) Ph-Qz-Kf-Mv-Ch-Di-Cc

Numbered lines refer to equilibria listed in table III-6.

Stable divariant assemblages are illustrated on the KAL projection. The dotted line is the P_{total} surface.

Figure III-20 Log fugacity H_2O vs. log fugacity CO_2 at 6000 bars and $600^{\circ}C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages

- (2) Ph-Qz-Kf-Tr-Cc-An-Ky
- (21) Ph-Qz-Mv-Ch-Cc-An-Ky
- (31) Qz-Mv-Kf-Cc-An-Ky
- (49) Ph-Qz-Kf-Mv-Ch-Tr-Cc
- (52) Qz-Ch-Tr-Cc-An-Ky
- (59) Ph-Qz-Kf-Tr-Cc-An-Zo
- (85) Ph-Qz-Mv-Ch-An-Cc-Zo
- (91) Ph-Qz-Mv-Ch-Tr-Cc-Zo
- (101) Ph-Qz-Kf-Mv-Tr-Cc-Zo
- (109) Qz-Ch-Cc-Tr-An-Zo
- (113) Qz-Mv-Kf-Cc-An-Zo

Numbered lines refer to equilibria listed in table III-6. Stable divariant assemblages are illustrated on the KAL projection. The dotted line is the P_{total} surface.

Figure III-21 Log fugacity H_2O vs. log fugacity CO_2 at 6000 bars and $800^\circ C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages

- (2) Ph-Qz-Kf-Tr-An-Sl-Cc
- (21) Ph-Qz-Mv-Ch-Cc-An-Sl
- (31) Qz-Mv-Kf-Cc-An-Sl
- (52) Qz-Ch-Tr-Cc-An-Sl
- (59) Ph-Qz-Kf-Tr-Cc-An-Zo
- (71) Ph-Qz-Kf-Ch-Tr-Cc-Zo
- (85) Ph-Qz-Mv-Ch-An-Cc-Zo
- (105) Ph-Qz-Mv-Kf-Ch-Cc-Zo
- (109) Qz-Ch-Cc-Tr-An-Zo
- (113) Qz-Mv-Kf-Cc-An-Zo

Numbered lines refer to equilibria listed in table III-6. Stable divariant assemblages are illustrated on the KAL projection. The dotted line is the P_{total} surface.

Figure III-22 Log fugacity H_2O vs. log fugacity CO_2 at 10000 bars and $400^\circ C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages

(23) Ph-Qz-Mv-Ch-Di-Cc-Ky

(33) Ph-Qz-Kf-Mv-Di-Cc-Ky

(46) Ph-Qz-Kf-Mv-Ch-Di-Cc

(115) Qz-Ch-Tr-Di-Cc-Ky

Numbered lines refer to equilibria listed in table III-6.

Stable divariant assemblages are illustrated on the KAL projection. The dotted line is the P_{total} surface.

Figure III-23 Log fugacity H_2O vs. log fugacity CO_2 at 10000 bars and $600^\circ C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages

- (30) Ph-Qz-Mv-Ch-Tr-Di-Cc
- (46) Ph-Qz-Kf-Mv-Ch-Di-Cc
- (55) Ph-Qz-Kf-Di-Cc-Ky-Zo
- (82) Ph-Qz-Mv-Tr-Di-Cc-Zo
- (84) Ph-Qz-Mv-Ch-Cc-Ky-Zo
- (91) Ph-Qz-Mv-Ch-Tr-Cc-Zo
- (98) Ph-Qz-Mv-Kf-Di-Cc-Zo
- (108) Qz-Cc-Ky-Tr-Ch-Zo
- (110) Qz-Mv-Kf-Ky-Cc-Zo
- (118) Qz-Tr-Di-Cc-Ky-Zo

Numbered lines refer to equilibria listed in table III-6. Stable divariant assemblages are illustrated on the KAL projection. The dotted line is the P_{total} surface.

Figure III-24. Log fugacity H_2O vs. log fugacity CO_2 at 10000 bars and $800^\circ C$ showing relationships among stable invariant assemblages. Numbers in circles refer to the invariant assemblages

-
- (2) Ph-Qz-Kf-Tr-Cc-An-Ky
 - (53) Qz-An-Cc-Ky-Zo
 - (59) Ph-Qz-Kf-Tr-An-Cc-Zo
 - (71) Ph-Qz-Kf-Ch-Tr-Cc-Zo
 - (84) Ph-Qz-Mv-Ch-Ky-Cc-Zo
 - (105) Ph-Qz-Mv-Kf-Ch-Cc-Zo
 - (108) Qz-Cc-Ky-Tr-Ch-Zo
 - (110) Qz-Mv-Kf-Ky-Cc-Zo

Numbered lines refer to equilibria listed in table III-6. Stable divariant assemblages are illustrated on the KAL projection. The dotted line is the P_{total} surface.

3 5

OF/DE

Figure III-25 Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 2000 bars for minerals appearing on the KAL projection.
Numbers in circles refer to the invariant assemblages

- (2) Ph-Qz-Kf-Tr-Cc-An-Ad
- (4) Ph-Qz-Kf-Di-Tr-Cc
- (12) Ph-Qz-Kf-Ch-Tr-Cc-An
- (21) Ph-Qz-Mv-Ch-Cc-An-Ad
- (31) Qz-Mv-Kf-Cc-An-Ad
- (48) Ph-Qz-Mv-Kf-Ch-Tr-An
- (52) Qz-Ch-Tr-Cc-An-Ad

Phlogopite plus quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The andalusite-sillimanite transition is from Holdaway(1971). The dotted line is the maximum stability of dolomite in the presence of phlogopite plus quartz.

10F

$P_{CO_2} + P_{H_2O} = 2000 \text{ bars}$

Sillimanite
Andalusite

Figure III-26. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 3000 bars for minerals appearing on the KAL projection. Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Ad
- (4) Ph-Qz-Kf-Di-Tr-Cc
- (21) Ph-Qz-Mv-Ch-Cc-An-Ad
- (27) Ph-Qz-Mv-Ch-Tr-Cc-An
- (31) Qz-Mv-Kf-Cc-An-Ad
- (37) Ph-Qz-Mv-Kf-Tr-Cc-An
- (49) Ph-Qz-Kf-Mv-Ch-Tr-Cc
- (52) Qz-Ch-Tr-An-Cc-Ad

Phlogopite plus quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The andalusite-kyanite and andalusite-sillimanite transitions are from Holdaway (1971). The dotted line is the maximum stability of dolomite coexisting with phlogopite plus quartz.

Figure III-27. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 4000 bars for minerals appearing on the KAL projection.

Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Sl
- (4) Ph-Qz-Kf-Di-Tr-Cc
- (21) Ph-Qz-Mv-Ch-Cc-An-Sl
- (27) Ph-Qz-Mv-Ch-Tr-Cc-An
- (30) Ph-Qz-Mv-Ch-Tr-Di-Cc
- (31) Qz-Mv-Kf-Cc-An-Sl
- (37) Ph-Qz-Mv-Kf-Tr-Cc-An
- (46) Ph-Qz-Kf-Mv-Ch-Di-Cc
- (52) Qz-Ch-Tr-Cc-An-Sl

Phlogopite and quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The kyanite-sillimanite transition is from Holdaway(1971). The dotted line represents the maximum stability of dolomite in the presence of phlogopite plus quartz.

T °C

550

600

650

700

6

3

15

$P_{CO_2} + P_{H_2O} = 4000 \text{ bars}$

39

650

700

550

600

Figure III-28. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 5000 bars for minerals appearing on the KAL projection.

Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Sl
- (4) Ph-Qz-Kf-Dl-Tr-Cc
- (21) Ph-Qz-Mv-Ch-Cc-An-Ky
- (27) Ph-Qz-Mv-Ch-Tr-Cc-An
- (30) Ph-Qz-Mv-Ch-Tr-Dl-Cc
- (31) Qz-Mv-Kf-Cc-An-Ky
- (37) Ph-Qz-Mv-Kf-Tr-Cc-An
- (46) Ph-Qz-Mv-Kf-Ch-Dl-Cc
- (52) Qz-Ch-Tr-Cc-An-Ky

Phlogopite plus quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The kyanite-sillimanite transition is from Holdaway(1971). The dotted line is the maximum stability of dolomite coexisting with phlogopite and quartz.

Figure III-29. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 6000 bars for minerals appearing on the KAL projection. Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Ky
- (4) Ph-Qz-Kf-Df-Tr-Cc
- (21) Ph-Qz-Mv-Ch-Cc-An-Ky
- (27) Ph-Qz-Mv-Ch-Tr-Cc-An
- (30) Ph-Qz-Mv-Ch-Tr-Df-Cc
- (31) Qz-Mv-Kf-Cc-An-Ky
- (46) Ph-Qz-Kf-Mv-Ch-Df-Cc
- (52) Qz-Ch-Tr-Cc-An-Ky
- (59) Ph-Qz-Kf-Tr-Cc-An-Zo
- (79) Ph-Qz-Mv-Tr-Cc-An-Zo
- (101) Ph-Qz-Kf-Mv-Tr-Cc-Zo
- (113) Qz-Mv-Kf-Cc-An-Zo

Phlogopite and quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The Kyanite-sillimanite transition is from Holdaway(1971). The dotted line represents the maximum stability of dolomite coexisting with phlogopite and quartz.

10F

$P_{CO_2} + P_{H_2O} = 6000 \text{ bars}$

Sillimanite
Kyanite

Figure III-30. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 7000 bars for minerals appearing on the KAL projection. Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Ky
- (4) Ph-Qz-Kf-Dl-Tr-Cc
- (30) Ph-Qz-Mv-Ch-Tr-Dl-Cc
- (31) Qz-Mv-Kf-Cc-An-Ky
- (53) Qz-Cc-An-Ky-Zo
- (59) Ph-Qz-Kf-Tr-Cc-An-Zo
- (83) Ph-Qz-Mv-Ch-An-Ky-Zo
- (84) Ph-Qz-Mv-Ch-Cc-Ky-Zo
- (91) Ph-Qz-Mv-Ch-Tr-Cc-Zo
- (101) Ph-Qz-Kf-Mv-Tr-Cc-Zo
- (108) Qz-Tr-Ch-Cc-Ky-Zo
- (111) Qz-Ch-Tr-An-Zo-Ky
- (113) Qz-Mv-Kf-Cc-An-Zo

Phlogopite and quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The kyanite-sillimanite transition is from Holdaway(1971). The dotted line represents the maximum stability of dolomite coexisting with phlogopite and quartz.

Figure III-31. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 8000 bars for minerals appearing on the KAL projection. Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Ky
- (4) Ph-Qz-Kf-Df-Tr-Cc
- (30) Ph-Qz-Mv-Ch-Tr-Df-Cc
- (31) Qz-Mv-Kf-Cc-An-Ky
- (53) Qz-Cc-An-Ky-Zo
- (59) Ph-Qz-Kf-Tr-Cc-An-Zo
- (82) Ph-Qz-Mv-Tr-Df-Cc-Zo
- (84) Ph-Qz-Mv-Ch-Cc-Ky-Zo
- (91) Ph-Qz-Mv-Ch-Tr-Cc-Zo
- (98) Ph-Qz-Mv-Kf-Df-Cc-Zo
- (108) Qz-Ch-Tr-Cc-Ky-Zo
- (111) Qz-Cf-Tr-An-Ky-Zo
- (113) Qz-Mv-Kf-Cc-An-Zo

Phlogopite and quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The kyanite-sillimanite transition is from Holdaway(1971). The dotted line represents the maximum stability of dolomite coexisting with phlogopite and quartz.

Figure III-32. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 9000 bars for minerals appearing on the KAL projection.

Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Ky
- (4) Ph-Qz-Kf-Dl-Tr-Cc
- (30) Ph-Qz-Mv-Ch-Tr-Dl-Cc
- (53) Qz-Cc-An-Ky-Zo
- (59) Ph-Qz-Kf-Tr-Cc-An-Zo
- (82) Ph-Qz-Mv-Tr-Dl-Cc-Zo
- (84) Ph-Qz-Mv-Ch-Cc-Ky-Zo
- (91) Ph-Qz-Mv-Ch-Tr-Cc-Zo
- (98) Ph-Qz-Mv-Kf-Dl-Cc-Zo
- (108) Qz-Ch-Tr-Cc-Ky-Zo
- (110) Qz-Mv-Kf-Cc-Ky-Zo
- (112) Qz-Mv-Kf-An-Ky-Zo

Phlogopite and quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The kyanite-sillimanite transition is from Holdaway(1971). The dotted line represents the maximum stability of dolomite coexisting with phlogopite and quartz.

Figure III-33. Temperature($^{\circ}\text{C}$) vs. X_{CO_2} at 10,000 bars for minerals appearing on the KAL projection. Numbers in circles refer to the invariant assemblages:

- (2) Ph-Qz-Kf-Tr-Cc-An-Ky
- (4) Ph-Qz-Kf-Di-Tr-Cc
- (30) Ph-Qz-Mv-Ch-Tr-Di-Cc
- (53) Qz-Cc-An-Ky-Zo
- (59) Ph-Qz-Kf-Tr-Cc-An-Zo
- (82) Ph-Qz-Mv-Tr-Di-Cc-Zo
- (84) Ph-Qz-Mv-Ch-Cc-Ky-Zo
- (91) Ph-Qz-Mv-Ch-Tr-Cc-Zo
- (98) Ph-Qz-Mv-Kf-Di-Cc-Zo
- (108) Qz-Ch-Tr-Cc-Ky-Zo
- (110) Qz-Mv-Kf-Cc-Ky-Zo

Phlogopite and quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. The kyanite-sillimanite transition is from Holdaway(1971). The dotted line represents the maximum stability of dolomite coexisting with phlogopite and quartz.

pressure metamorphism (i.e., contact metamorphism) in the presence of biotite plus quartz.

III-6 TEMPERATURE FLUID COMPOSITION DIAGRAMS

Isobaric temperature-fluid composition diagrams can now be derived. The computer program XCDFOR (Skippen and Yzerdraat, 1970) was used to calculate the positions of the curves. Equilibrium relations are calculated in the same manner as for the log-fugacity diagrams. These diagrams have been calculated at 1000 bar intervals from 2000 to 10,000 bars and are shown on figures III-25 to III-33.

Previously, there were considered to be six types of reactions which plotted on a temperature-fluid composition diagram (Greenwood, 1962). They are

- 1) dehydration reactions, i.e., reactions of the type:

where H_2O is present on the high temperature side of the reaction.

- 2) decarbonation reactions, i.e., reactions of the type:

where CO_2 is present on the high temperature side of the reaction.

- 3) hydration-decarbonation reactions, i.e., reactions of the type:

where CO_2 is present on the high temperature side of the reaction and H_2O is present on the low temperature side of the reaction.

- 4) carbonation-dehydration, i.e., reactions of the type:

where H_2O is on the high temperature side of the reaction and CO_2 is on the low temperature side.

- 5) dehydration-decarbonation, i.e., reactions of the type:

where both H_2O and CO_2 are on the high temperature side of the reaction.

- 6) solid-solid reactions, i.e., reactions of the type:

where no volatiles are present as phases in the reaction.

A new type of reaction was found to exist on the temperature-fluid composition diagrams calculated in this work, i.e., a hydration reaction. Reaction 39, i.e.

is an example of this type (see figure III-32) with water on the low temperature side of the reaction. On a temperature-fluid composition diagram, the shape of a hydration reaction is a mirror image of a dehydration reaction (see figure III-34).

Dolomite would be a stable mineral in some bulk compositions within the temperature and pressure ranges included in figures III-23 through III-33. The dotted lines on these figures represent the reactions

These reactions correspond to the upper stability limit of dolomite on the $T-X_{CO_2}$ diagrams. However, below these lines, dolomite-quartz would be stable in place of tremolite-calcite and all assemblages including tremolite-calcite below these dotted reactions on the $T-X_{CO_2}$ diagrams would be metastable.

Zoisite becomes stable on the $T-X_{CO_2}$ diagrams above 5 kilobars on the water-rich part of the diagrams. As pressure increases, however, the stability field of zoisite expands into the higher CO_2 region as can be seen in figures III-29 to III-33. Zoisite and

Figure III-34. Schematic temperature vs. X_{CO_2} diagram showing a theoretical dehydration reaction and a theoretical hydration reaction.

diopside coexist only above 8 kilobars.

Epidote is a common mineral in calcsilicate rocks, and is found even in low-pressure rocks of the albite-epidote-hornfels facies. The addition of ferric iron to the epidote structure increases its stability field, so that the presence of iron-rich epidotes in contact aureoles is not inconsistent with zoisite being present on the $T-X_{CO_2}$ diagrams only at high pressures. In the Whetstone Lake area (Carmichael, 1970), epidote is present in the calcareous rocks except where diopside is present. Crawford (1972) reports a biotite-clinozoisite-quartz assemblage in a contact aureole from California, but never with diopside. The assemblage biotite-quartz-zoisite is reported from the Alps (Ackermann and Raase, 1973) but again diopside is absent. The assemblage biotite-hornblende-diopside-epidote-potassic feldspar-plagioclase-quartz does exist in the Mattawa area, and high pressures can therefore be inferred.

The invariant assemblage, biotite-calcite-quartz-potassic feldspar-calcium amphibole-diopside which characterizes invariant point 4 has been found near Mattawa, in the Selkirk Mountains (Hoy, 1974), and in the Whetstone Lake area (Carmichael, 1970). The sequence of reactions around the invariant point has been verified in the field by Hoy (1974), Thompson (1974) and Williams-Jones (1973). The aluminosilicate polymorph which is stable with this invariant assemblage varies. In Mattawa it is kyanite; within the Selkirk Mountains (Hoy, 1974) and at Whetstone Lake (Carmichael, 1970) the stable aluminosilicate is sillimanite. These observations suggest that invariant point 4, if projected onto a P-T diagram,

must pass through both the sillimanite and kyanite stability fields. Using the experimental data described earlier in this chapter to calculate $T-X_{CO_2}$ diagrams for the end member minerals, invariant point 4 does not pass through the sillimanite field. This means either that the experimental data require tighter bracketing, or else the phases used in the calculations are not a sufficiently close approximation to those in the field. The position of invariant point 4 is determined by the intersection of reactions 1 and 2. As these reactions intersect at a very small angle, on a $T-X_{CO_2}$ diagram, small errors in the position of the reactions could make large differences in the position of invariant point 4.

There are many other minerals which could be stable within the temperature, pressure and bulk-compositional restrictions of the $T-X_{CO_2}$ diagrams. These include: talc, dolomite, enstatite, forsterite, anthophyllite, serpentine, grossularite, margarite, pyrope, and cordierite; these minerals are not found in the Mattawa area and so have been neglected in the present study. Also, every additional mineral added to the model, substantially increases the number of possible invariant points, so only a selected number of minerals could be chosen.

One critical assemblage found on the $T-X_{CO_2}$ diagram is biotite-quartz-tremolite-kyanite. At lower pressures, the stability of this assemblage is primarily dependent on the value of X_{CO_2} , being restricted to the CO_2 -rich portion of the $T-X_{CO_2}$ diagram. As pressure increases, the stability of biotite-quartz-tremolite-kyanite expands until at 10 kilobars, this assemblage becomes stable in the pure water system above $690^{\circ}C$. The assemblage biotite-quartz-

hornblende-kyanite-plagioclase-garnet is found in the Mattawa area but is a rare assemblage. The occurrence of this assemblage is restricted to the Cahill Lake area (Map 3) where its occurrence is indicated by the symbol "Ky". The calculated $T-X_{CO_2}$ diagrams suggest that this assemblage could be more widespread than it is known to be at the present time. One possible controlling factor is that in the field, the observed magnesium silicate mineral is garnet while on the calculated diagrams the corresponding mineral is chlorite. It is therefore possible that reactions involving garnet which have not been considered in this study, restrict the stability field of kyanite-tremolite in nature.

III-7. PRESSURE-TEMPERATURE DIAGRAMS

A pressure-temperature diagram with water pressure equal to total pressure has been constructed and is shown on figure III-35. The positions of the curves were calculated using XCDFOR (Skippen and Yzerdraat, 1970) for $X_{CO_2} = 0$. From this diagram it is readily seen that the stability of zoisite is controlled by the intersection of the two reactions

Reaction 61 limits the zoisite stability to temperatures greater than 550°C and reaction 34 to pressures greater than 5.5 kilobars.

Reaction 75:

which occurs at the same temperature as invariant point 4 does not pass through the sillimanite field on the calculated P-T diagram. This demonstrates that reaction 75 must occur at higher temperatures in the field than is shown on figure III-35 to enable invariant point 4 to pass through the sillimanite field.

Figure III-35. P_{H_2O} vs. temperature($^{\circ}C$) for non-carbonate minerals on the KAL projection. Numbers in circles refer to the invariant assemblages:

- (48) Ph-Qz-Mv-Kf-Ch-Tr-An
- (50) Ph-Qz-Mv-Kf-Ch-Di-Tr
- (83) Ph-Qz-Mv-Kf-An-Ky-Zo
- (90) Ph-Qz-Mv-Ch-Tr-An-Zo
- (100) Ph-Qz-Mv-Kf-Tr-An-Zo
- (102) Ph-Qz-Mv-Kf-Di-Tr-Zo
- (111) Qz-Ch-Tr-An-Ky-Zo
- (112) Qz-Mv-Kf-An-Ky-Zo

Phlogopite and quartz are stable with every assemblage. Numbered lines refer to equilibria listed in table III-6. Aluminosilicate relationships are after Holdaway(1971).

10F

CHAPTER IV COMPARISON BETWEEN FIELD ASSEMBLAGES AND CALCULATED PHASE RELATIONS

IV-1 INTRODUCTION

Calculated phase-equilibria diagrams are often used to relate isograds observed in the field with experimentally determined equilibrium conditions. The above approach has been relatively successful when comparing isograds found in marbles with equilibrium diagrams calculated from experimental work (Trommsdorff, 1972; Hewitt, 1937b; Moore and Kerrick, 1976; Rice, in press). The minerals found in marbles, however, are close to their ideal end-member compositions. The aluminous calcsilicate minerals found in the Mattawa area are substantially different from the ideal end-members. Hornblende, for example, is not very similar to tremolite in composition, but it is considered to be the equivalent of tremolite on the calcsilicate grid. As changing the compositions of the minerals on the grid changes the position of the equilibrium curve, it is readily seen that the calcsilicate grids do not relate directly to the field. This chapter is concerned with the problem of correlating assemblages found in the field with equilibrium conditions as calculated on the $T-X_{CO_2}$ diagrams.

IV-2 COMPARISON OF FIELD ASSEMBLAGES AND THE IDEAL CALCSILICATE GRID

In the Mattawa area, a common assemblage is biotite - calcite - quartz - potassic feldspar - hornblende - epidote - plagi-

clase, i.e., assemblage 2 on table II-6. The locations at which this assemblage was observed in the field are shown on map 6 through 8. This assemblage also corresponds to invariant point 59 on the $T-X_{CO_2}$ diagrams (figures III-29 through III-33). Further petrologic observations that help to correlate field assemblages with the grids include the presence of a muscovite breakdown reaction in the area, the fact that migmatites are present, and the presence of kyanite as the stable aluminosilicate mineral throughout the area. These four conditions must be taken account of in relating the field areas with the calculated equilibrium model.

Figure IV-1 is a polybaric $T-X_{CO_2}$ diagram with pertinent experimental data shown. The position of the isobaric invariant point 59 (i.e., phlogopite - calcite - quartz - potassic feldspar - tremolite - zoisite - anorthite) is plotted at various pressures. Also plotted on figure IV-1 is the intersection of the two reactions:

at various pressures. The intersection of these two curves is not an isobaric invariant point because the two reactions take place in rocks of different bulk composition. The trace of the intersection of reactions 1 and 3, represents the conditions under which both equilibria 1 and 3 could hold simultaneously in adjacent rocks of suitable bulk composition. In other words, if we have the assemblage phlogopite - calcite - quartz - potassic feldspar - tremolite

Figure IV-1 Temperature ($^{\circ}\text{C}$) vs. X_{CO_2} at various pressures for the intersection of end-member equilibria 1 and 26 (curve A) and end-member equilibria 1 and 3 (curve B).

Curve A represents the conditions under which the assemblage phlogopite - calcite - quartz - potassic feldspar - tremolite - anorthite - zoisite is stable.

Curve B represents the conditions under which the assemblage phlogopite - calcite - quartz - potassic feldspar - tremolite is stable alongside the assemblage muscovite - quartz - potassic feldspar - kyanite. The sillimanite - kyanite transition is from Holdaway (1971) and the minimum melting of granite curve is from Piwinskii (1968).

in the calcsilicate rocks and adjacent to it, the assemblage muscovite - quartz - potassic feldspar - kyanite in the psammite or pelitic rocks, then the conditions of formation for the two rocks must lie on the trace of the intersection of the two curves.

The equilibria used on Figure IV-1 are for the ideal end-members. If the real minerals found in the Mattawa area behaved as ideal end-members, the conditions for the formation of the observed assemblages would be close to the intersection of curves A and B on figure IV-1. The pressure would then be between 7 and 8 kilobars and the temperature slightly above 650°C. The kyanite - sillimanite transition is also plotted for 7.75 kilobars and indicates that the intersection of curves A and B should be in the kyanite stability field. Also plotted on figure IV-1 is the approximate position of the minimum melting of granite at 10 kilobars (Piwinskii, 1968). The minimum melting curve of granite at 7.75 kilobars would be at higher temperatures than plotted on figure IV-1. For ideal end-members, however, the conditions of formation lie nowhere close to the minimum melting curve, and, as there are abundant migmatites in the Mattawa area, it is apparent that the minerals in the rocks are not behaving as ideal end-members.

IV-3. ACTIVITY - COMPOSITION RELATIONS

Except for plagioclase (Orville, 1972), biotite (Wones and Eugster, 1965) and calcite (Gordon and Greenwood, 1970), the

activity-composition relations of the minerals involved in the equilibria are not well known. A solution model was therefore chosen to approximate the activity-composition relations in hornblende, potassic feldspar, biotite, epidote and diopside. The model chosen assumes ideal solution on more than one lattice site and was first discussed by Temkin (1945), and introduced into the geological literature by Ringwood (1958).

In the case of the equilibrium $T-X_{CO_2}$ diagrams, (figure III-25 through III-33), all of the mineral phases were pure end-members, with only a single component dissolved to a significant extent in a mineral phase. The activities of components dissolved mainly in solids were taken to be unity. In the actual rocks, this is not the case. In order to apply the equilibrium model to field assemblages, it is therefore necessary to include terms in the equilibrium constant to account for varying activities of components dissolved in solids.

Activity-composition relations in plagioclase have been studied experimentally by Orville (1972) and these data are used to approximate the activity-composition relations of the plagioclase. Using the Temkin model, activities of the remaining minerals were calculated by the following formulae:

$$a_{Ca_2Mg_5Si_8O_{22}(OH)_2}^{Hb} = \left(\frac{Ca}{2}\right)^2 \left(\frac{Mg}{5}\right)^5 \left(\frac{Si}{8}\right)^8 \left(\frac{OH}{2}\right)^2$$

(Scheme A) a

$$a_{Ca_2Mg_5Si_8O_{22}(OH)_2}^{Hb} = \left(\frac{3 - Ca - Na - K}{1}\right) \left(\frac{Ca}{2}\right)^2 \left(\frac{Mg}{5}\right)^5 \left(\frac{Si}{8}\right)^8 \left(\frac{OH}{2}\right)^2$$

(Scheme B) b

Scheme B for calculating the activity of tremolite in hornblende has been used by Allen (1976) in an attempt to account for the change in activity brought about by the increasing occupancy of the A site in tremolite.

The general formula for epidote is written as $\text{Ca}_4(\text{Al}, \text{Fe}^{3+})_2\text{Al}_4\text{Si}_6\text{O}_{24}(\text{OH})_2$, e.g. Deer, Howie, and Zussman (1960). Holdaway (1972) and Liou (1973) describe the composition of an epidote as the percentage of a theoretical pistacite molecule of the formula $\text{Ca}_4\text{Fe}_6^{3+}\text{Si}_6\text{O}_{24}(\text{OH})_2$. However, no natural epidotes have been found which have a pistacite content greater than 33 percent and the highest content of ferric iron in a synthetic epidote was 35 percent (Holdaway, 1972; Liou, 1973). Dollase (1973), studying Mossbauer spectra of epidote-group minerals, found that of the three octahedral sites available for ferric iron, more than 85 percent was found in the M(3) octahedral site. Therefore, it is

suggested that the iron epidote end-member should be represented by $\text{Ca}_4\text{Fe}_2^{3+}\text{Al}_4\text{Si}_6\text{O}_{24}(\text{OH})_2$, and that the amount of iron end-member should be calculated on the basis of this formula. Thus an epidote with 33 percent pistacite molecule (Ps_{33}) in the nomenclature of Holdaway, is taken in this study to have zero percent clinozoisite molecule, i.e., Cz_0 , rather than Cz_{67} . This approach has a significant effect on the activity-composition relations. Since ferric iron is taken to substitute into only two positions in the unit cell, rather than the six which are usually assumed, the activity of zoisite in epidote has been calculated according to equation f. No account has been taken of the shift in symmetry from orthorhombic for zoisite to monoclinic for clinozoisite. As no calorimetric data exist for zoisite and clinozoisite, and thermodynamic parameters derived from hydrothermal experimental work are ambiguous (Holdaway, 1972), no information is available on the change in the thermodynamic parameters with the shift in symmetries. There should, however, be a measurable difference which would in turn affect the position of the recalculated curve.

IV-4 CALCULATION IN THE SHIFT OF THE EQUILIBRIUM CURVES DUE TO SOLID SOLUTION

Using the previously described methods, the activities of components in rocks were calculated from electron microprobe analysis of minerals (see table IV-1). Specimens B-604-73 and Y from the Mattawa area and three samples from the Whetstone Lake area were chosen for these detailed studies. The samples from the

Table IV-1. Activities of minerals from rocks in the Mattawa area (B-604-73 and Y) and from the Whetstone Lake area (A110, A545, A500) from Carmichael, 1970.

Mineral	A110	A545	A500	B-604-73	Y
Hb (Scheme A)*	1.530×10^{-3}	1.092×10^{-3}	9.240×10^{-2}	1.091×10^{-3}	4.362×10^{-3}
Hb (Scheme B)*	4.270×10^{-4}	3.932×10^{-4}	6.505×10^{-2}	4.998×10^{-4}	3.136×10^{-3}
Biotite	5.044×10^{-3}	3.066×10^{-3}	9.310×10^{-2}	2.533×10^{-3}	1.927×10^{-2}
Potassic feldspar	0.910	0.877	0.879	0.845	n.d.
Calcite	0.975	0.957	0.955	n.d.	n.d.
Epidote	0.01285	0.04086	0.02140	0.145	n.p.
Plagioclase	0.20	0.35	0.44	0.45	0.53

n.d. not determined

n.p. not present

* Schemes A and B refer to activities calculated according to equation a and b, respectively.

Whetstone Lake area have been reported by Carmichael (1970) and include the sample numbers A110, A500 and A545.

The mineral assemblage for samples B-604-73, A110, A545, and A500 is biotite - calcite - quartz - potassic feldspar - hornblende - epidote - plagioclase and this assemblage corresponds to the isobaric invariant 59 (see figures III-25 to III-33). The conditions under which this assemblage is stable can be calculated from the simultaneous solution, or the intersection of two of the equilibria involved in the isobaric invariant point 59. The two equilibria used are:

The assemblage from sample A144 (Carmichael, 1970) is biotite - calcite - quartz - potassic feldspar - hornblende - diopside - plagioclase and so corresponds to the isobaric invariant point 4 (see figures III-25 to III-33). The conditions of equilibrium for this assemblage can be calculated from the intersection of the two equilibria:

However, these two equilibria intersect at a very sharp angle so that small errors in the calculated positions of the curves would lead to large errors (greater than $\pm 80^\circ\text{C}$) in the position of the

intersection of the two curves. For this reason no attempt is made to calculate the metamorphic conditions from this assemblage.

The assemblage of sample Y, biotite - quartz - hornblende - plagioclase - kyanite - potassic feldspar, corresponds to the isobaric univariant assemblage represented by equilibrium 39:

The position of this equilibrium along with other criteria will help restrict the possible conditions of metamorphism.

The values of the gas fugacity product for each of equilibria 1, 26 and 39 have been calculated using the method described in section IV-2 with the activities summarized in table IV-2. The positions of the equilibrium curves in T-P- X_{CO_2} space have been calculated using the computer program, XCDFOR (Skippen and Yzerdraat, 1970).

IV-5 CALCULATIONS FROM THE WHETSTONE LAKE AREA, ONTARIO

Figure IV-2 is a P-T plot of the simultaneous solution of equilibria 1 and 26 for samples A110, A545, and A500 (Carmichael, 1970). This diagram illustrates the possible range of conditions under which the assemblage biotite - calcite - quartz - potassic feldspar - plagioclase - epidote - hornblende is in equilibrium for rocks A110, A545 and A500. The solid lines on figure IV-2 represent the equilibrium conditions calculated using the hornblende solid-solution model A, (see equation a, section IV-3) and the dotted

Table IV-2. Gas fugacity products for equilibria 1, 26, and 39.

Equilibrium 1. Activity of tremolite component calculated from scheme A of section IV-3.

	A	B	C
B-604-73	-31362.	62.159	.8004
A110	-31362.	62.040	.8004
A545	-31362.	62.148	.8004
A500	-31362.	64.235	.8004
Y	-31362.	66.049	.8004

Equilibrium 1. Activity of tremolite component calculated from scheme B of section IV-3.

	A	B	C
B-604-73	-31362.	61.142	.8004
A110	-31362.	60.416	.8004
A545	-31362.	60.817	.8004
A500	-31362.	63.778	.8004
Y	-31362.	65.619	.8004

Table IV-2 cont'd.

Equilibrium 26. Constants calculated from the data of Ackerman and Karl (1972).

	A	B	C
B-604-73	-1041.	.552	.3459
A110	-1041.	.567	.3459
A545	-1041.	.348	.3459
A500	-1041.	- .230	.3459

Equilibrium 26. Constants calculated from data of Orville (personal communication).

	A	B	C
B-604-73	1012.	-2.398	.3463
A110	1012	-2.383	.3463
A545	1012.	-2.002	.3463
A500	1012.	-3.180	.3463

Table IV-2 cont'd.

Equilibrium 39.

	A	B	C
Sample Y			
(scheme A)*	-3648.	.685	-.7092
Sample Y			
(scheme B)**	-3648.	.749	-.7092

* activity of tremolite component in hornblende calculated from equation a, section IV-3.

** activity of tremolite component in hornblende calculated from equation b, section IV-3.

Figure IV-2 Pressure and temperature for the stability of the assemblage biotite - calcite - quartz - potassic feldspar - hornblende - plagioclase - epidote in samples A110, A545 and A500 from the Whetstone Lake area (Carmichael, 1970). Solid lines are conditions calculated from tremolite activities according to equation a, section IV-3. Dashed lines are conditions calculated from tremolite activities according to equation b, section IV-3. Aluminosilicate relationships after Holdaway (1971) and Richardson et al. (1969). Zoisite data for calculations are from the data of Ackermann and Karl (1972).

lines represent the stability conditions calculated using the hornblende solid-solution model B (see equation b, section IV-3). The results shown on figure IV-2 are not consistent with the known field relationships. Sample A110 is from the kyanite zone while samples A545 and A500 are from the sillimanite zone. Sample A110, which the calculations show as having the highest equilibrium temperature, should, according to the field data of Carmichael (1970), have the lowest.

The inconsistency between the calculated P-T curves for rocks from Whetstone Lake and the known field relationships suggests that a problem may exist in the experimental data used to calculate the calcsilicate model. A review of the experimental data presented in chapter III indicates that all of the experimental data met stringent tests of internal consistency except for the data of Ackermann and Karl (1972) for zoisite equilibria (section III-3.5). In view of possible inconsistencies in the zoisite data, it was decided to use an alternative set of data. Johannes and Orville (personal communication to G. Skippen) have measured the following equilibrium constant:

$$26. \quad 2\text{Zo} + \text{CO}_2 = 3\text{An} + \text{Cc} + \text{H}_2\text{O}$$

$$\log K_{26} = -\frac{320}{T} - \frac{0.3463 (P-1)}{T} + 2.6$$

This expression for the equilibrium constant has been used in place of the data of Ackermann and Karl to calculate the position of assemblage 59 in P-T space with the results shown on figure IV-3.

Figure IV-3 Pressure and temperature of the assemblage, biotite - calcite - quartz - potassic feldspar - hornblende - plagioclase - epidote, for samples A110, A545, A500 from the Whetstone Lake area (Carmichael, 1970). Solid lines are calculated from tremolite component activities according to equation a, section IV-3. Dashed lines are conditions from tremolite component activities according to equation b, section IV-3. The shaded area indicates the uncertainties in the positions of the aluminosilicate reactions. Zoisite data for calculations are from the data of Orville and Johannes (personal communication).

Also shown on figure IV-3 are the aluminosilicate relationships as calculated by Holdaway (1971) and Richardson et al. (1969) with their uncertainty limits. The data of Holdaway are used in subsequent diagrams.

Within the uncertainties of the position of the kyanite - sillimanite transition, the assemblage of sample A110 would be in equilibrium (by scheme A) in the Kyanite zone and the assemblage of sample A545 would be in equilibrium (by scheme A) in the Sillimanite zone. The calculated conditions of equilibrium for sample A500 plot nowhere near the others, so sample A500 is not considered further.

The calculations using the activity of tremolite component from scheme A are more consistent with the kyanite - sillimanite transition than the calculations from scheme B. For this reason the activity of tremolite component from scheme A will be used in all subsequent calculations.

IV-6 CALCULATIONS FROM THE MATTAWA AREA

A limited amount of chemical data for rocks from the Mattawa area is currently available. The objective of this section is to use the available analytical data for samples B-604-73 and Y (table II-5) to make a preliminary description of the metamorphic environment near Mattawa, and to illustrate the way in which the equilibrium model developed in chapter III can be applied to areas such as Mattawa in which a sequence of metamorphic isograds has not been developed.

The approach to be followed is illustrated on figure IV-4, an isobaric $T-X_{CO_2}$ section for 10 kilobars. The positions of equilibria 1 and 26 on a $T-X_{CO_2}$ section have been solved by computer for the mineral compositions of sample B-604-73. Since these two equilibria must apply simultaneously to specimen B-604-73, then this specimen is constrained to the intersection of equilibria 1 and 26 at point A on figure IV-4. Point A is analogous to invariant point 59 on the $T-X_{CO_2}$ sections of Chapter III.

Specimen Y is similarly constrained to curve 39 on figure IV-4. It is not possible to further restrict sample Y to a point on the diagram because only a single equilibrium from the calculated model of chapter III applies to this specimen. It is possible, however, to place additional limits on the stability of sample Y by considering equilibrium 3. At temperatures below those plotted for curve 3, the assemblage, potassic feldspar - kyanite - vapour reacts to form muscovite plus quartz. Sample Y which contains kyanite and potassic feldspar, cannot therefore exist beneath curve 3 in the presence of a vapour phase. The position of curve 3 in figure IV-4 has been plotted for end-member mineral phases. The principal impurity in muscovite and potassic feldspar is sodium, which would shift the actual position of curve 3 to lower temperatures since sodium would stabilize potassic feldspar over muscovite. This shift, however, is not likely to be very large. Thus, point C, corresponding to invariant point 35 in the equilibrium model, is taken to give a minimum temperature and water content for sample Y at 10 kilobars.

Figure IV-4 Temperature ($^{\circ}\text{C}$) vs. X_{CO_2} at 10,000 bars for the equilibria

Numbers with circles are invariant points. Dashed lines are metastable extensions of reactions.

The position of equilibrium 3 on figure IV-4 is also of interest in relation to point A. A muscovite-out isograd occurs in psammitic rocks between Crocan Lake, represented by sample B-604-73, and Cahill Lake, represented by sample Y. In the presence of a fluid phase, the conditions for reaction 3 must occur in the area between the localities of samples B-604-73 and sample Y. Although further chemical data would be required for minerals from psammitic rocks in order to precisely locate curve 3 for such rocks, it is of interest to compare the position of curve 3 for end-member minerals with points A and C on figure IV-4. Point B indicates the intersection of curves 3 and 1 and point E indicates the fluid content of psammitic rocks that would be required for muscovite to be stable at the temperature of point A. A comparison of point B with points A and C suggests that a gradient in temperature between Crocan and Cahill Lakes could not account for the muscovite-out isograd at a total pressure of 10 kilobars.

An additional curve shown on figure IV-4 shows the conditions necessary for the breakdown of tremolite to enstatite, quartz and diopside. Point D marks the intersection of an amphibole breakdown reaction with equilibrium 1 and provides an approximation for the beginning of the granulite facies in rocks B-604-73 and Y.

The approach described in the previous paragraphs is further developed on figure IV-5, a polybaric $T-X_{CO_2}$ section. The curves labelled A, B, C, D on this figure show the polybaric traces of points analogous to A, B, C and D from figure IV-4. The coincidence of curves A, B, and C on this figure results from the

algebraic independence of any two of the three curves. The assumption of end-member mineral compositions for reaction 3 at both points B and C requires this coincidence. In order to plot curve B independently of curves A and C, it would be necessary to measure the actual compositions of minerals in psammitic rocks adjacent to each of samples B-604-73 and Y.

Figure IV-6 shows the information from figure IV-4 on a P-T diagram. Since curves A and C are virtually superimposed in P-T space, only curve A has been plotted on figure IV-6. Also indicated by dotted curves on figures IV-5 and IV-6 are the limits of uncertainty arising from experimental data used to calculate curves A and B. The uncertainty in curve C is much larger as it is derived from the position of the dependent equilibrium 39 as calculated by equation 24 in section III-4.

From the figures, IV-4 to IV-6, some conclusions about the conditions of metamorphism can be reached. Since muscovite - quartz - fluid is stable in psammitic rocks adjacent to sample B-604-73, then the position of point A can only be stable at lower values of X_{CO_2} than indicated by curve 3. This statement depends, however, on the assumption of a common fluid phase in psammitic and calcsilicate rocks; if the fluid phase is not the same in both rock types, then it is not possible to limit the stability of sample B-604-73 by reference to curve 3.

The equilibrium conditions for sample Y are taken to be at higher values of X_{CO_2} and temperature than indicated by curve C on figure IV-5. At the same time, the stability of sample B-604-73 has tentatively been placed along curve A and beneath

Figure IV-5 Temperature ($^{\circ}\text{C}$) vs. X_{CO_2} at various pressures for rocks from the Mattawa area.

Curve A is the intersection of equilibria 1 and 26 showing conditions of stability of the assemblage biotite - calcite - quartz - potassic feldspar - epidote - plagioclase - hornblende, for sample B-604-73.

Curve B is the intersection of equilibrium 1 calculated for sample B-604-73 and the end-member equilibrium 3.

Curve C is the intersection of equilibrium 39 calculated for sample Y and the end-member equilibrium 3.

Curve D is the intersection of equilibrium 1 for sample B-604-73 and the ideal tremolite breakdown curve.

The dotted lines beside curves A and B show the uncertainty in the position of the curve calculated from the uncertainties in the experimental data.

The numbers by the dots on the curves indicate the pressure in kilobars

Figure IV-6 Temperature ($^{\circ}\text{C}$) vs. pressure (kilobars) in the Mattawa area. Curve A shows the intersection of equilibria 1 and 26 which is the stability condition for sample B-604-73, i.e. the assemblage, biotite - calcite - quartz - potassic feldspar - hornblende - epidote - plagioclase. Curve B is the intersection of equilibrium 1 for sample B-604-73 and the end-member equilibrium 3. Curve D is the intersection of equilibrium 1 for sample B-604-73 and the end-member tremolite breakdown. The kyanite - sillimanite transition is from Holdaway (1971). The dotted lines illustrate the experimental uncertainties in the positions of the curves. The numbers by the dots on the curves indicate the pressure in kilobars.

the intersection of curves A and B. These observations, by themselves, fail to place limits on the conditions of metamorphism. It may be recalled from Chapter II, however, that field mapping demonstrated the absence of isograds in calcsilicate rocks and indicated, therefore that strong regional gradients in intensive parameters did not exist in the Mattawa area. The significance of this observation can be emphasized by reference to figure IV-5. A large gradient in X_{CO_2} would have been required between Crocan and Cahill Lakes to stabilize samples B-604-73 and Y at temperatures lower than $700^{\circ}C$. Such a gradient would have resulted in a mappable isograd in the calcsilicate rocks as observed by Carmichael (1970) in the Whetstone Lake area. These observations suggest that metamorphic conditions could not have been significantly lower than the coincidence of curves A and C on figure IV-5, i.e.

Pressure: 8.5 kilobars

Temperature: $725^{\circ}C$

X_{CO_2} : 0.32

The weakest assumption that leads to the above estimate is the use of a common fluid phase for psammitic rocks adjacent to calcsilicate B-604-73. It is possible that X_{CO_2} in the carbonate-bearing calcsilicate was higher than the carbonate-free psammites. If this were the case, then the conditions for the formation of sample B-604-73 could have exceeded the values suggested by the coincidence of curves in figure IV-5. On this basis, it is suggested that the values obtained from the coincidence of curves on

figure IV-5 should be cited only as a minimum value for metamorphic conditions in the Mattawa area.

More chemical data on more samples would give more complete information on the metamorphic conditions in the Mattawa area. For example, the assemblage muscovite - calcite - quartz - potassic feldspar - epidote - plagioclase is found and is an isobaric invariant assemblage as is sample B-604-73. A unique curve for its equilibrium conditions could be found and plotted in a similar way to curve A on figures IV-4 to IV-6. With a large number of such curves from different assemblages in proximal and distal spatial relationships, the equilibrium conditions for the Mattawa area could be more precisely determined.

IV-7 THE RELATIONSHIP BETWEEN PARTIAL MELTING AND THE MINERAL ASSEMBLAGES IN THE MATTAWA AREA

As migmatites are common in the Mattawa area, it is of interest to consider the relationships among appropriate melting curves and the observed mineral assemblages. This can partially be accomplished by plotting the data of Kadik and Eggler (1975) for the reaction:

on a $T-X_{\text{CO}_2}$ diagram. This reaction, when plotted on a $T-X_{\text{CO}_2}$ diagram (figure IV-7), has the shape of a hydration reaction. The positions of the other melting curves have been estimated by taking

Figure IV-7 Temperature ($^{\circ}\text{C}$) vs. X_{CO_2} at 9000 bars for the equilibria:

1. biotite - calcite - quartz - potassic feldspar - hornblende (sample B-604-73)
26. epidote - plagioclase - calcite (sample B-604-73)
59. stability conditions for sample B-604-73.
39. biotite - plagioclase - quartz - potassic feldspar - hornblende - kyanite (for sample Y).
3. ideal end-member equilibrium $\text{Mv} + \text{Qz} = \text{Kf} + \text{Ky} + \text{H}_2\text{O}$
- A. $\text{Ab} + \text{Kf} + \text{Qz} + \text{V} = \text{L}$ (Boettcher and Wyllie, 1968)
- B. $\text{Mv} + \text{Qz} + \text{Ab} + \text{V} = \text{Als} + \text{L}$ (Kerrick, 1972)
- C. $\text{Mv} + \text{Kf} + \text{Qz} + \text{V} = \text{L}$ (Storre and Karotke, 1971)
- D. $\text{Kf} + \text{Qz} + \text{V} = \text{L}$ (Lambert et al., 1969)
- E. $\text{Mv} + \text{Qz} + \text{V} = \text{Als} + \text{L}$ (Storre and Karotke, 1971)
- F. $\text{Kf} + \text{Qz} + \text{Als} + \text{V} = \text{L}$ (Lambert et al., 1969)
- G. $\text{Ab} + \text{Kf} + \text{Qz} + \text{V} = \text{L}$ (Boettcher and Wyllie, 1968)

reaction $\text{Ab} + \text{V} = \text{L}$ (Kadik and Eggler, 1975)

The position of the reaction $\text{Ab} + \text{V} = \text{L}$ is accurately known whereas the position of the other melting reactions have been extrapolated from their positions in the pure water system. The kyanite - sillimanite transition is from Holdaway (1971). The dotted lines illustrate the experimental uncertainty in the position of the curves.

the temperature of melting in the pure H_2O system and extrapolating into $CO_2 - H_2O$ fluids by using the measured slope for the melting of albite. Other melting curves which are shown on figure IV are:

- A $Ab + Kf + Qz + V = L$ (Boettcher and Wyllie, 1968)
- B $Mv + Ab + Qz + V = Ky + L$ (Kerrick, 1972)
- C $Mv + Kf + Qz + V = L$ (Storre and Karotke, 1971)
- D $Kf + Qz + V = L$ (Lambert et al., 1969)
- E $Mv + Qz + V = Ky + L$ (Storre and Karotke, 1971)
- F $Kf + Qz + Ky + V = L$ (Lambert et al., 1969)

The relationships among these melting reactions in the pure water system are shown on figure IV-8. The topology of this diagram is based on the work of Lambert et al., (1969). The invariant point "Q" is from his nomenclature. The relationships of the albite-present reactions have been determined by Kerrick (1972).

The breakdown of muscovite in psammitic rocks of the Mattawa area is associated with the appearance of kyanite and the generation of a melted phase. In the presence of a vapour phase, equilibrium 3 and a number of additional equilibria involving a melt would apply to the process. The assemblage of the Psammitic Gneiss in which the muscovite-out isograd occurs is essentially muscovite - quartz - microcline, so that albite is present mainly as a component in the potassic feldspar. The first melting reaction which would produce melting in a rock of this composition would be reaction A, but at a higher temperature as albite is not present as a pure phase. This means that the actual conditions of the onset

Figure IV-8 Melting relationships for the assemblage albite -
potassic feldspar - quartz - muscovite - kyanite - H_2O in the pure
water system.

- A. $Ab + Kf + Qz + V = L$ (Boettcher and Wyllie, 1968)
- B. $Mv + Qz + Ab + V = Als + L$ (Kerrick, 1972)
- C. $Mv + Kf + Qz + V = L$ (Storre and Karotke, 1971)
- E. $Mv + Qz + V = Als + L$ (Storre and Karotke, 1971)
- F. $Kf + Qz + Als = L$ (Lambert et al., 1969)
- G. $Ab + Kf + Qz + V = L$ (Boettcher and Wyllie, 1968)
- 3. $Mv + Qz = Kf + Ky + L$ (Chatterjee and Johannes, 1974)

The aluminosilicate relations are from Holdaway (1971). The
relationships around invariant point Q, were derived by Lambert
et al., (1969) and around invariant point K, by Kerrick (1972).

of melting would be somewhere between the positions of reactions A and C.

The position of point K_1 is not precisely known at present due to a lack of experimental data. The partitioning of Na between potassic feldspar and muscovite would cause K_1 to be shifted away from the position of equilibrium 3 for pure potassium phases. A rock consisting of the phases, muscovite - quartz - potassic feldspar - kyanite - liquid - vapour, would be constrained to a univariant curve joining K_1 with Q_1 . The compositions of phases would change with increasing temperature along the univariant K_1Q_1 until one of the phases disappeared.

The psammitic rocks from the Crocan Lake area must have formed at conditions beneath those indicated by curves A and 3 on figure IV-7. The disappearance of muscovite and the appearance of kyanite and a melted phase in the Cahill Lake area indicates that metamorphic conditions lay above those of the univariant K_1Q_1 . Further experimental studies to locate the univariant K_1Q_1 would be of considerable use in studying the metamorphic petrology of the Mattawa area.

If the fluid phase in the individual rock types in the Mattawa area is internally buffered, then some possible paths of metamorphism, similar to the type of path described by Greenwood (1975), can be seen on figure IV-9. If we start with conditions at point A and increase the temperature and pressure, then the path of metamorphism will follow curve 1 until it reaches point C, from where it could branch onto path 1b or 1a. This would depend on the bulk composition of the rock. If at point C the modal

Figure IV-9 Schematic temperature and pressure vs. X_{CO_2} diagram for calcsilicate and psammitic rocks. Solid lines represent stability boundaries and dashed lines represent proposed metamorphic paths.

amount of calcite exceeded the modal amount of epidote, then the path would follow curve 1b. If the reverse were true, the path would follow curve 1a. If the path follows 1a, it will soon reach point E which is the start of melting. Here, if it has more epidote than granitic material it will follow path 1a¹, but if it has more granitic material, then it will branch along curve 1a to follow the melting curve to higher values of X_{CO_2} . It will reach the muscovite breakdown curve at point F. Again a choice of paths is available, depending on the composition, i.e. along to path 1c¹ or continuing along the melting curve until eventually point B, the stability limit of hornblende, is reached.

If at point C the path of metamorphism continued along path 1b, then a similar pattern develops. At point D the path could branch to follow path 1c or continue along curve 1b. If no muscovite was in the rock, then the path would follow curve 1b to point H. If there was muscovite in adjacent rocks, it would break down and might externally buffer the assemblage along curve 1c to point G and so to the melting curve. From point H the path of metamorphism would follow curve 1b to point B. Thus point B can be reached with or without anatexis. As point B represents the stability limit of hornblende, it is clear that metamorphic conditions in the Mattawa area have not reached that far.

Figure IV-10 illustrates a possible sequence of events during high-grade metamorphism for assemblages similar to those in the Mattawa area, as seen on a pressure temperature diagram. The assemblage corresponding to invariant point 57 (table III-2) would in fact be at least divariant. Not only could the X_{CO_2}

Figure IV-10 Schematic pressure vs. temperature diagram showing relationship between metamorphic paths, and possible isograd sequences. Also shown is the relationship between melting curves and the stability of hornblende. Y and Z are arbitrary values of X_{CO_2} such that $Z > Y$. They would be equal to the values of X_{CO_2} where the melting curve intersects the hornblende breakdown curve.

of the fluid phase change, but also the composition of the minerals in the assemblage can change. This means that within limits, as pressure and temperature change, the compositions of the minerals and X_{CO_2} for the assemblage can change to maintain chemical equilibrium.

Three possible paths of metamorphism are shown on figure IV-10, a high pressure-low temperature gradient (curve 1), a high temperature low pressure gradient (curve 2) and an intermediate pressure and temperature gradient (curve 3). If the metamorphic course follows curve 1 or 2, then the Ca-amphibole-potassic feldspar isograd would be seen in the field. If it follows curve 3, however, such an isograd would not exist. If the course of metamorphism follows curve 3 on figure IV-10, it would remain on the line until anatexis. If the initial melting begins on melting curve L, (i.e., potassic feldspar - plagioclase - quartz - liquid - vapour) then the composition of the fluid would change to higher values of X_{CO_2} and the assemblage 59 would become unstable upon reaching the stability curve of hornblende at point A on figure IV-10, with a value of X_{CO_2} greater than some value Z. If, however, the composition of the rock was slightly different, and its initial melting conditions were on curve M, i.e., muscovite - quartz - potassic feldspar - liquid - vapour, then the hornblende stability would not be reached until point B on figure IV-10, where X_{CO_2} is equal to some value Z. If the rock does not reach its minimum melting point before the hornblende breakdown curve, then the hornblende will break down at point C on figure IV-10, with a value of X_{CO_2} equal to some value Y when the value of Y is less than the value of Z. Thus the bulk

composition of the quartzo - feldspathic portion of the rock is a major factor in determining the conditions at which orthopyroxenes become stable. The lower the melting temperature of the rock, then if a large proportion of melt is produced, the higher will be the value of X_{CO_2} and the lower will be the temperature of formation of orthopyroxene.

IV-8 THE RELATIONSHIP BETWEEN THE GRANULITE FACIES AND THE MATTAWA AREA

The beginning of the granulite facies is often marked by a zone in which hornblende coexists with diopside and orthopyroxene. For these rocks the following equilibrium must hold:

This equilibrium has been studied by Boyd (1959) and the constants for this equilibrium, as calculated by Skippen (1971), are used to plot its position on figure IV-7. The position of this equilibrium can be used to approximate the beginning of the granulite facies. The activities of components in natural assemblages in the rock would have to be known to calculate the exact position of the curve.

Activity coefficients of coexisting pyroxenes were calculated by Froese and Gordon (1974) for granulite facies rocks from Quairading, Australia. Hornblende was also present in these rocks, but no analysis is available for the hornblende. The calculated activities of diopside and orthopyroxene were in the order

of 1, but the activity of $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ in hornblende, would be in the order of 10^{-2} to 10^{-4} because of the high Al content of hornblende in high grade metamorphic rocks. (See for example, table IV-1). Therefore the controlling factor in the calculation of a curve to fit assemblages from the field is hornblende. As the activity of $\text{Ca}_2\text{Mg}_5\text{Si}_8\text{O}_{22}(\text{OH})_2$ in hornblende is in the denominator of equation (2) (Chapter III), the effect of solid solution on the B value of the gas fugacity product will be in the order of +2 to +4. This will move the position of the tremolite breakdown curve on figure IV-5 and IV-7 to lower temperatures. Thus the ideal position of the tremolite breakdown curve, would be a maximum estimate for the start of the granulite facies.

The intersection of the tremolite breakdown with the position of equilibrium 1, recalculated for specimen B-604-73 is shown on figures IV-4 and IV-6. For an actual granulite facies rock, the temperature of the amphibole breakdown curve would be lower, and this would move the trace of the intersection with equilibrium 1 to lower values of temperature and X_{CO_2} . Thus the start of the granulite facies, i.e., the initial stability of orthopyroxene in rocks of similar composition to the calcsilicates in the Mattawa area, must be at lower temperatures than curve D on figure IV-6.

Different methods of arriving at the Ca-amphibole stability limit have already been discussed and illustrated on figures IV-9 and IV-10. Reaching points A, B or C on figure IV-10 are in effect the start of the granulite facies, so it can be seen that the metamorphic conditions at the onset of the granulite facies are dependent

on the bulk composition of the quartzo-feldspathic component of the rock.

Before the breakdown of hornblende, biotite plus quartz could react to form potassic feldspar plus enstatite, but consideration of such equilibria is beyond the scope of this thesis. All the phase relations of Mg-silicates would need to be determined before the exact sequence of events leading to the formation of granulites could be evaluated. In the Mattawa area, metamorphic conditions have not reached those of the granulite facies.

SUMMARY AND CONCLUSIONS

Geological mapping has been carried out in a high-grade metamorphic terrain to the northwest of Mattawa, Ontario. Five geological maps have been prepared as follows:

- Map 1: Geology of the Crocan Lake area, scale 1/8 inch to 1 mile.
- Map 2: Geology of the Timber Lake area, scale 1/4 inch to 1 mile.
- Map 3: Geology of the Cahill Lake area, scale 1/4 inch to 1 mile.
- Map 4: Geology of the Miner's Lake area, scale 1/4 inch to 1 mile.
- Map 5: Compilation Map of the Mattawa - North Bay - Temiscaming area, scale 1:50,000.

In addition, three maps displaying the mineral assemblages in calc-silicate rocks have been compiled as follows:

- Map 6: Assemblage map of the Crocan Lake area, scale 1/8 inch to 1 mile.
- Map 7: Assemblage map of the Mattawa - North Bay - Temiscaming area, scale 1:50,000.
- Map 8: Assemblage map of the northeast portion of the Ontario Gneiss Segment, scale 1:250,000.

The rocks of the Mattawa area have been divided into three main units, the Butler Gneiss, the Antoine Gneiss, and the Jocko Gneiss. The Butler Gneiss, a very siliceous unit, has been subdivided into two further units. The first is the Cahill Lake sequence which is a thick sequence of dominantly psammitic gneisses with interlayered amphibolite. The second, the Crocan Lake sequence, has been further

subdivided into the following units: Marble, Pyrrhotite Gneiss, Pelitic Gneiss, Calcsilicate Gneiss, and Psammitic Gneiss.

The Antoine Gneiss is a migmatitic - biotite - oligoclase gneiss which has tentatively been placed above the Butler Gneiss in the stratigraphic sequence.

The Jocko Gneiss is a granite gneiss which has been intruded into both the Butler and Antoine Gneisses.

Four phases of folding have been recognized. F_1 is recumbent and isoclinal with variable axial trends. F_2 is tight and upright with axial traces parallel to F_1 . F_3 is also tight and upright with both northwest and northeast axial trends. F_4 is open with an upright northeast-trending axial plane.

The most common assemblages in the calcsilicate rocks are:

- 1) biotite - calcite - quartz - hornblende - plagioclase - epidote.
- 2) biotite - calcite - quartz - potassic feldspar - plagioclase - hornblende - epidote.
- 3) biotite - quartz - potassic feldspar - hornblende - plagioclase - epidote.

These are the same assemblages that are shown by Carmichael, (1970) to be related to a mineral isograd in the Whetstone Lake area. The isograd mapped by Carmichael was related to the following reaction:

biotite + calcite + quartz $\rightarrow$ potassic feldspar + Ca-amphibole +

$\text{CO}_2 + \text{H}_2\text{O}$

These mineral assemblages in the Mattawa area do not exhibit any systematic pattern in their distribution and an isograd could not therefore be mapped in the Mattawa area.

The mapping of mineral assemblages in other rock types did indicate the presence of a muscovite-out isograd in the area between Crocan Lake and Cahill Lake. Muscovite is a ubiquitous mineral in psammitic rocks in the vicinity of Crocan Lake but is replaced by microcline and kyanite in psammites of the Cahill Lake area. Difficult access to the area between Crocan and Cahill Lakes precluded a detailed study of this isograd.

In addition to the field studies described above, a theoretical study of the metamorphism of the calcsilicate rocks was undertaken.

In the system $\text{CaO} - \text{MgO} - \text{KAlSi}_3\text{O}_8 - \text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{CO}_2 - \text{H}_2\text{O}$, 74 mineral reactions can be written involving volatiles along with the minerals phlogopite, muscovite, potassic feldspar, clinoclase, tremolite, diopside, calcite, zoisite, anorthite, and aluminosilicate. If the phase relations are restricted to assemblages that involve quartz, fluid and phlogopite in excess, then 120 isothermal, isobaric invariant points are possible. Six independent equilibria are required to calculate the equilibrium constants of all 74 reactions.

A substantial number of experimentally studied reactions has been reported in the literature. As an aid in selecting the experimental data to be used in this study, thermodynamic theory was used to test the internal consistency of reported experimental data. The data were first required to be consistent with respect to the logarithm of the equilibrium constant plotted against reciprocal temperature. Secondly, a standard entropy of reaction was calculated and used to normalise the enthalpy of reaction

for each experimental point to one bar and 25°C (Fisher and Zen, 1971). The experimental data were required to produce a consistent value for the standard enthalpy change of solid phases. The following six reactions were chosen by this method.

- 1) $5\text{Ph} + 6\text{Cc} + 24\text{Qz} = 5\text{Kf} + 3\text{Tr} + 6\text{CO}_2 + 2\text{H}_2\text{O}$ (Hoschek, 1973)
- 2) $\text{Tr} + 3\text{Cc} + 2\text{Qz} = 5\text{Di} + 3\text{CO}_2 + \text{H}_2\text{O}$ (Skippen, 1971)
- 3) $\text{Mv} + \text{Qz} = \text{Kf} + \text{Ad} + \text{H}_2\text{O}$ (Chatterjee and Johannes, 1974)
- 4) $\text{Mv} + \text{Cc} + \text{Qz} = \text{Kf} + \text{An} + \text{CO}_2 + \text{H}_2\text{O}$ (Hewitt, 1974)
- 5) $\text{Mv} + 2\text{Zo} + \text{Qz} = \text{Kf} + 4\text{An} + 2\text{H}_2\text{O}$ (Ackermann and Karl, 1972)
- 6) $5\text{Mv} + 3\text{Ch} = 5\text{Ph} + 8\text{Ky} + \text{Qz} + 12\text{H}_2\text{O}$ (Bird and Fawcett, 1973)

Of these six reactions, number 5 did not meet the requirement of having no dependence of the standard enthalpy change of solids on temperature. However, accurate thermodynamic data are not available for zoisite so it is impossible at the present time to properly evaluate this reaction.

The six independent reactions were used to calculate the equilibrium constants for the 68 dependent reactions. Log-fugacity of H_2O vs. log-fugacity CO_2 diagrams were calculated as a way of graphically displaying the equilibrium constants, and to determine which reactions and invariant points were stable, after the method of Korzhinskii, 1959. Temperature - mole fraction CO_2 diagrams have also been constructed as an aid to the study of the calcsilicate assemblages.

Electron microprobe analyses of calcsilicate assemblages have been used in conjunction with a Temkin model to calculate the activities of various components in the minerals. These activities

have been combined with the experimentally determined equilibrium constants to calculate an equation that expresses the equilibrium conditions for a particular rock specimen. Analytical data have been collected for only two specimens in the study but these data suggest that the minimum values of pressure and temperature of metamorphic rocks in the Mattawa area are:

Pressure: 8.4 kilobars

Temperature: 725°C

It is further concluded that the breakdown of muscovite in the Mattawa area is associated with partial melting. The actual muscovite breakdown may take place along a univariant in $T - X_{\text{CO}_2}$ space which involves the assemblage, muscovite - quartz - plagioclase - potassic feldspar - kyanite - vapour - melt. This univariant should exist over a temperature range so a sharply defined muscovite-out isograd may not exist in the Mattawa area. This interpretation requires the presence of an $\text{H}_2\text{O} - \text{CO}_2$ fluid.

It is also concluded that rocks containing minerals which have large free energies of mixing may not develop isograds. This is due to the combined factors that both X_{CO_2} and the compositions of the minerals can adjust to maintain the phases in chemical equilibrium. Thus gradients in pressure, temperature and gas composition could exist over large areas of gneissic terrain, but go completely unnoticed due to the lack of any change in the mineral assemblages. The only way to measure changes in the metamorphic conditions in such areas would be to document the changes in the activities of the components in rocks of the same assemblage. These changes in

activities could be equated to changes in metamorphic conditions by the use of an equilibrium model such as developed in this study.

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Appendix I Mineral assemblages from the Mattawa area.

CALC-SILICATE

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
T-5	x	x		x				x	x							
B-71-8		x		x												
B-71-9	x	x	x				x	x	x				x	x		
B-71-17	x		x		x		x		x			x	x			
B-71-26			x					alt	x				x			Gs
B-71-27		x	x	x				alt	x				x			Cb
B-71-35			x	x				x	x				x			Gs, Sc
B-71-35d		x		x				x	x				x			Al, Op
B-71-41	x	x						x	x	x			x	x		
B-71-54		x							x	x						
B-71-77	x	x					x		x							
		x	x	x	x				x							Sc
B-71-78		x	x		x			x	x							
B-71-83		x	x	x	x				x				x			Op
B-71-91a	x	x	x					x	x							Op
B-71-101	x	x	x			x		x	x				x			
B-2-72	x	x	x		x	x	x	x								
B-4-72		x	x	x	x				x				x			
B-7-72	x	x	x		x		x	x	x				x	x		
B-8-72	x	x	x		x		x	x	x				x			
B-9-72		x	x	x				x	x				x		x	
B-11-72		x	x			x		x	x				x	x		
B-15-72	x	x	x		x	Mg		x	x				x	x		Sc
B-16-72		x	x	x	x	x		x	x					x		Tr

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-17-72		x	x					28	x					x		Ox
B-18-72	x		x		x	x		x				x		x		Am
B-20-72		x	x						x							Ox
B-23-72	x		x				x	Pt	x				x	x	x	
B-24-72	x	x	x					x	x				x	x		Op
B-25-72		x				x		32				x		x		Ox
B-26-72	x	x	x				x	40	x						x	
altered			x		x			x								
B-29-72	x	x	x		x			x	x			x				
B-32-72	x	x			x	x	x	28	x				x	x	x	Op
B-38-72	x	x			x	x		32	x					x		Cp
B-39-72	x		x				x	28					x	x		Op
B-43-72	x	x	x		x			22					x	x	x	
B-48-72	x	x	x					35	x				x	x	x	
B-54-72		x	x		x		x	x	x				x			
B-55-72	x	x			x		x	x	x				x	x		
B-58-72	x	x	x		x		x	x	x				x	x		Op
B-60-72	x	x	x		x		x	x	x							
B-64-72a	x		x		x			22-32		x		x			x	Ox
B-66-72	x	x	x					38	x				x		x	
B-67-72	x	x					x	28	x				x	x	x	
B-68-72	x	x					x	x	x	x						
B-69-72	x	x	x	x	x	x		35	x				x	x	x	Sc
B-71-72	x	x	x		x	x		30	x				x	x		Op
B-72-72	x	x	x				x	x	x				x	x		

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-73-72	x	x	x			x	x	37	x					x	x	
B-74-72	x	x	x		x	x		33	x				x			Op, Sc
B-81-72		x	x						x				x			Sc, Ox
B-82-72		x	x			x		x	x				x			
B-83-72	x	x			x	x		45	x				x	x		Sc
B-90-72	x	x	x	x	x			25	x					x	x	Op
B-123-72		x	x	x				x	x						x	
B-128-72	x	x	x				x	32	x					x	x	Op
B-130-72	x	x	x				x	31	x	x				x		Op
B-131-72	x	x	x				x	42	x					x		Op
B-132-72	x	x	x			x	x	40	x	x			x	x	x	
B-147-72	x	x					x	x	x				x	x	x	Op, Il Mt.
B-154-72		x	x	x				x	x	x						Sc, Bo
B-157-72		x	x	x	x			alt	x	Gs ₅₀						
B-160-72		x	x	x				31 45	x				x			
B-161-72		x	x	x	x				x				x			
B-162-72		x	x		x	x		45	x	x		x				
B-164-72	x	x		x	x		x	x	x					x		
B-179-72	x	x	x			x		x	x			x				Op
B-182-72	x	x	x		x		x	x	x					x	x	
B-183-72	x	x	x		x	x	x	x	x				x	x		Ox
B-187-72	x	x					x	x	x					x	x	Ox
B-191-72	x	x	x				x	x	x					x		Ox
B-192-72	x	x	x		x	x	x	x	x				x	x	x	
B-195-72	x	x	x			x	x	x	x							Ma, Ca

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-198-72	x	x	x		x	x	x	32					x	x	x	
B-199-72	x	x	x					x								
B-200-72	x	x	x				x	x	x				x	x		Mt, Il
		x	x	x				x	x				x	x		Mt, Il
B-202-72	x	x	x		x	x			x				x		x	Op
B-204-72	x			x	x		x	x					x			alt
B-213-72b	x	x			x			x	x							Ox
	x							x	x							Cm, Gs, Ox
B-213-72d					x		x	x	x				x			Ph, Tr
B-215-72	x	x	x				x	x	x				x	x		Op
B-216-72	x	x	x				x	x	x							
B-217-72	x	x	x		x		x	x	x				x	x	x	
B-218-72	x				x	x		x	x			x				
B-222-72	x	x	x	x			x	x	x				x	x		
B-223-72		x	x					alt	x							Op
B-228-72	x	x	x				x	x	x				x			
B-230-72	x	x			x								x	x		Mt, Il
B-231-72	x	x	x			x	x	x					x	x	x	
B-232-72			x		x	x			x				x			
B-233-72	x				x			x		x		x				Cz
	x	x			x			x	x				x	x	x	Op
B-234-72	x	x						x	x	x	x			x	x	Mt, Il
B-237-72	x	x	x		x	x	x	x	x							
B-241-72	x	x	x	x			x	x	x	x						
B-242-72	x	x	x			?	x		x					x	x	

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky ¹	Mv	Sp	Ap	Zr	Other
B-243-72		x	x	x			t	x	x				x		x	
B-244-72	x		x		x		x	x	x	x				x	x	Op
B-248-72	x		x						x							
B-263-72	x		x		x		x	x	x				x	x	x	Op
B-268-72	x	x				x		x	x							
B-270-72	x	x			x		x	x	x				x	x	x	
B-275-72	x	x	x	x	x	x		45	x	x			x	x		Op
B-277-72	x	x	x	x	x			x	x				x		x	Sc
B-278-72	x	x	x				x	x	x					x		Op
B-279-72		x	x					x		x			x			
B-280-72		x	x	x				x	x	x			x	x	x	
B-281-72		x	x			x		x	x		x		x			
B-284-72	x	x	x	x			x	x	x				x			
B-285-72	x	x	x		x	x		x						x		0x
B-286-72	x	x	x		x	x	x	x	x					x		Op
B-287-72	x		x		x		x	30	x					x	x	
B-289-72	x	x	x	x	x			x	x							Sc
B-290-72	x		x		x		x	x	x			x	x			
B-291-72	x	x	x				x	x	x				x			0x
		x	x		x				x							
B-292-72		x	x	x				x	x	x			x			Op
B-294-72		x	x				x	x	x	x						
B-295-72	x	x	x	x		x	x	x	x							Di-Bi
B-296-72		x	x				x	x	x							Sc,Op
B-297-72		x	x	x			x	x	x							Sc,Op

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-300-72	x	x				x	x	x	x				x	x	x	Op
B-308-72	x	x	x			x	x	x	x				x			
B-360-72	x	x	x				x	x	x				x	x	x	
B-382-73		x	x	x	x				x							
B-385-73	x		x					x	x	x						
B-387-73		x	x		x				x							Gr, Sc
		x	x					x	x				x			Gr
B-420-73	x	x			x			x	x	x				x		
B-456-73	x		x				x	x	x				x	x	x	Op
B-463-73		x	x	x	x			x	x				x			Op
B-467-73		x	x	x				x	x				x			Op
B-468-73		x	x						x				x	x		Op
B-469-73	x	x	x				x	x	x							
B-483-73	x	x	x					x	x					x		
B-510-73		x	x		x			x	x				x			
B-511-73	x	x					x	x	x					x		
B-512-73	x	x	x				x	x	x				x			
B-513-73	x	x	x				x	x	x							
		x	x	x				x	x							
B-514-73		x	x			x			x							
B-515-73	x	x	x		x		x	x	x				x	x	x	
B-516-73	x	x	x				x	x	x						x	Op
B-517-73	x	x	x				x	x	x					x		Sc, Op
B-518-73	x	x	x		x	x	x	x	x					x		Op
B-519-73		x	x	x				x	x				x			Op

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-519-73	x	x	x				x	x	x							
B-520-73		x	x	x				x	x				x			
B-522-73	x				x		x		x							
B-523-73		x	x			x	x	x	x				x	x	x	
B-524-73	x	x	x		x	x	x	x	x					x	x	Op
B-526-73	x	x	x				x	x	x				x	x		
B-527-73	x	x	x				x	x	x				x	x	x	
B-531-73	x		x				x	x	x					x	x	Op
B-532-73	x	x	x				x	x	x							Ox
B-533-73	x	x	x		x	x	x	x	x							
B-547-73	x	x	x		x		x	x	x				x	x	x	
B-548-73	x	x	x		x		x	x	x				x	x	x	
B-549-73		x	x	x				x	x							
B-551-73	x	x						x	x				x			
B-553-73	x	x	x				x	x	x				x	x	x	
B-554-73	x	x			x	x	x	x	x	x						
B-555-73	x	x	x				x	x	x	x			x		x	
B-558-73	x	x	x				x	x	x				x	x	x	
B-559-73		x	x			x		x	x				x			
B-560-73	x	x	x		x		x	x	x					x	x	
B-561-73	x	x	x				x	x	x				x	x	x	
B-562-73	x	x				x		x	x	x				x	x	Op, Rt
B-563-73	x	x			x	x	x	x	x							Ox
B-564-73	x	x						x	x	x			x	x		Op
B-565-73	x	x	x		x	x	x	x	x					x		Op

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-568-73	x	x	x				x	x	x				x			
B-569-73	x	x			x	x	x	x	x					x	x	Op
B-570-73	x	x	x	x			x	x	x				x			
B-571-73	x	x	x				x	x	x				x	x	x	
B-572-73	x		x		x			x	x	x						Op
B-573-73	x	x	x				x		x				x	x		
B-574-73	x	x	x			x	x	x	x				x	x	x	Op
B-575-73	x	x	x			x	x	x	x				x	x	x	Op
B-576-73	x	x					x	x	x					x	x	
B-578-73	x	x	x		x		x	x	x					x	x	
B-579-73	x	x	x		x		x	x	x	x			x	x	x	
B-580-73	x	x	x		x			x	x				x	x	x	
B-581-73	x	x			rr	x		x	x							0x
B-583-73	x	x	x			x	x	x	x				x	x		
B-584-73	x	x	x				x	x	x				x	x	x	Op
B-585-73	x	x	x				x	x	x				x	x	x	
B-586-73	x		x		x		x	x	x						x	
B-587-73	x	x	x		x	x	x	x	x				x			
B-588-73		x	x					x	x							Bi-Di
	x	x		x		x		x	x							
B-589-73		x	x	x				x	x				x			
B-590-73	x	x	x				x	x	x					x	x	
B-591-73		x	x					x	x	x			x			
B-592-73	x	x	x					x	x	x			x		x	
B-593-73	x	x					x	x	x					x		

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
																Sc
B-594-73	x	x					x		x							
B-595-73	x	x	x		x	x	x	x	x					x	x	
B-596-73	x	x	x		x		x	x	x					x	x	
B-598-73	x	x					x	x	x							
B-599-73	x	x					x	x	x					x	x	
B-600-73	x	x	x				x	x	x					x	x	
B-601-73	x	x	x				x	x	x					x	x	x
B-602-73	x	x	x				x	x	x					x	x	x He
B-603-73	x	x	x		x		x	x	x					x	x	x
B-604-73	x	x	x		x		x	x	x					x	x	x
B-605-73	x	x	x				x	x	x					x	x	x
B-606-73	x	x	x				x	x	x					x	x	x
B-608-73	x	x	x			x	x	x	x					x	x	x Op
B-609-73	x	x					x	x	x					x	x	
B-612-73	x	x							x							
B-613-73	x	x					x	x	x					x	x	x
B-614-73	x	x	x				x	x	x					x		x
B-616-73	x	x	x					x	x							
B-617-73	x	x					x	x	x						x	x
B-618-73	x	x					x	x	x							Op
B-621-73	x	x			x	x	x	x	x					x	x	Op
B-622-73	x	x	x		x	x	x	x	x							Op
B-623-73	x	x	x		rr	x	x	x	x						x	x
B-624-73		x	x						x	x				x		
B-625-73	x	x	x		x		x	x	x						x	Op

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-627-73		x	x				x	x	x					x		Op
		x	x	x				x	x				x			
B-628-73		x	x			x		x	x							x
B-630-73	x	x	x				x	x	x				x	x	x	
B-633-73	x	x	x		x		x	x	x				x	x	x	
B-634-73	x	x	x		x		x	x	x				x	x	x	
B-635-73	x	x	x				x	x	x				x	x	x	He
B-636-73		x	x		x			x	x				x			Op
B-637-73	x	x	x		x	x	x	x							x	Op
B-638-73	x	x	x				x	x	x							x Op
B-639-73	x	x	x		x	x	x	x	x						x x	Op
		x	x					x	x						x x	
B-640-73	x	x	x		x	x	x	x	x				x	x	x	Sc
B-641-73	x	x	x		x		x	x	x				x	x		
B-643-73	x	x			x	x		x	x						x	
B-644-73	x		x					x	x	x						x Sc, Op
B-645-73	x	x	x		x		x	x	x				x	x	x	
B-646-73	x	x	x				x		x				x	x	x	Sc
B-647-73	x	x	x		x	x	x	x	x				x			
B-648-73	x		x				x	x	x				x	x	x	
B-649-73	x	x	x				x	x	x				x			
B-651-73	x	x	x		x		x	x	x				x			
B-657-73	x	x	x				x	x	x						x x	
B-658-73	x	x	x				x	x	x						x x	Op
B-659-73	x	x	x				x	x	x				x	x	x	

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-661-73	x	x	x				x	x	x				x	x	x	
B-662-73	x	x	x		x		x	x	x				x	x	x	Sc, He
B-663-73	x	x			x	x			x	x						He
B-665-73		x			x	x		x	x	x						
B-666-73			x			Fe		alt	x							He
B-667-73	x	x	x					x	x	z			x	x	x	Op
B-668-73	x				x	x		x	x	x						
B-669-73	x	x			x			x	x	x				x		Op
B-671-73	x	x			x	x	x	x					x	x		
B-672-73	x	x		x	x			x	x	x				x	x	Op
B-673-73	x	x			x		x	x	x				x	x	x	
B-674-73	x	x						x	x				x			
B-675-73		x	x		x			x	x				x			
B-676-73	x	x		x			x	x						x	x	Bi-Di
B-677-73	x	x					x	x	x	x			x	x	x	
B-678-73		x				x		x	x					x		Op
B-679-73	x	x				x		x	x				x	x		
B-680-73	x	x	x		x	x		x	x					x		Sc, He
B-681-73	x	x				x		x	x					x	x	
B-685-73	x		x				x		x			x			x	Op
B-691-73	x	x						x	x	x				x	x	Op
B-693-73		x				x		x	x						x	
B-697-73	x	x				x		x	x					x	x	Rt
B-699-73	x	x	x			x	x	x	x				x			
B-730-73	x	x	x		x		x	x	x	x				x	x	

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-731-73	x	x				x	x	x	x				x	x	x	Op
B-732-73	x	x	x			x	x	x	x				x	x	x	
B-733-73		x	x	x				x	x				x			Op
B-734-73	x		x				x	x	x				x	x	x	
B-735-73	x		x				x	x	x				x	x	x	Mt,Il
B-736-73		x			x	x		x	x	x		x	x		x	
B-737-73		x	x		x			x	x				x	x		
B-738-73	x	x	x			x	x	x	x				x	x		Op
B-739-73 alt		x	x			x	x	alt	x					x	x	
B-740-73	x	x	x				x	x	x				x	x	x	
B-741-73	x		x			x	x	x	x				x	x	x	
B-742-73	x	x	x	x			x	x	x				x			Mt,Il
B-744-73	x	x	x				x	x	x				x	x	x	
B-745-73	x	x			x				x	x		x		x		Op
B-746-73		x				x		x	x					x	x	
B-747-73	x	x	x	x	x	x		x	x					x		Cp
B-748-73	x	x	x	x				x	x							Op
B-749-73	x		x		x			x	x				x	x	x	
B-750-73		x	x	x	x			x	x					x		
B-751-73	x	x	x		x	x	x	x	x						x	Op
B-752-73	x	x	x		x			x	x					x	x	
B-754-73	x	x	x		x		x	x	x				x	x	x	
B-755-73	x	x	x				x	x	x				x	x	x	
B-756-73	x	x	x		x		x	x	x							
B-757-73		x	x			x	x	x								

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-758-73	x		x				x	x				x	x	x	x	
B-759-73	x	x	x				x	x	x				x	x	x	
B-760-73	x	x	x				x	x					x	x	x	
B-761-73	x	x	x				x	x	x				x	x	x	
B-763-73	x	x	x			x		x	x					x		Op
B-764-73	x	x	x	x			?	x	x				x	x	x	Mt,Il
B-765-73	x		x				x	x	x			x			x	Op
B-766-73	x		x				x	x	x			x		x		
B-767-73	x	x	x				x	x	x					x	x	Op
B-769-73	x	x	x				x	x	x				x	x	x	
B-770-73	x	x	x				x	x	x				x	x	x	
B-771-73	x	x			x			x	x				x	x		
B-773-73	x	x	x				x	x	x					x	x	
B-775-73		x	x	x					x				x	x		
B-778-73	x	x					x	x	x					x	x	Op
B-781-73	x		x			x		x	x			x	x	x		Op
B-784-73	x	x	x	x				x	x	x			x		x	
B-802-73	x	x		x			x	x	x					x		Bi-Di
B-808-73	x		x			x	x	x	x							
TMG-1-73	x		x					x	x					x	x	
TMG-2-73	x	x	x					x	x						x	
TMG-3-73	x		x			x	x	x	x	x				x	x	
TMG-5-73	x	x	x					x	x				x		x	
TMG-6-73	x	x	x		x			x	x				x		x	
TMG-8-73	x	x	x	x	x		x		x				x	x		

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
TMG-9-73	x	x	x		x		x	x	x				x	x		
TMG-10-73	x	x	x	x	x		x		x							x
TMG-14-73	x	x	x						x			x				x
TMG-19-73	x	x			x		x	x	x				x	x		Sc
TMG-24-73	x				x		x	x	x					x		Po, Sc, Cp
TMG-28-73	x	x	x	x	x				x	x						
TMG-30-73	x			x	x				x							Gs
GF-3-73	x	x	x		x		x	x	x				x			
GF-4-73	x	x	x		x			x	x				x			
GF-5-73	x		x				x	x	x			x				x
GF-6-73	x		x				x	x	x			x	x	x		
GF-8-73	x		x					x	x			x				x
GF-9-73	x	x	x		x		x	x	x				x	x		
GF-10-73	x	x	x		x		x	x	x						x	x
GF-12-73	x	x	x		x		x	x	x						x	x
GF-13-73	x		x				x	x	x				x			
GF-14-73	x	x			x		x	x	x							
GF-15-73	x	x	x				x	x	x				x	x		
GF-16-73		x	x			x			x							
GF-17-73	x	x	x		x		x	x	x				x			x
GF-18-73	x	x	x				x	x	x				x	x		x
GF-19-73	x		x		x		x	x	x				x	x		x
Gf-20-73	x	x	x	x	x		x	x	x				x	x		x
GF-21-73	x	x	x				x	x	x				x	x		x
GF-23-73	x	x	x			x			x	x			x	x		Op

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
GF-24-73	x	x					x	x	x				x	x	x	
GF-25-73		x	x	x				x	x				x		x	
GF-26-73		x					?	x	x				x		x	
GF-27-73	x	x	x		x		x	x								

OTHER

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-71-12				x				x								Opx, Id
B-71-21							x	x	x			x				
B-71-28	x	x						x	x	Al						
B-71-38	x	x						x	x	x			x			
B-71-39a	x	x					x	x	x	x						Op
B-71-42																Di, Opx, Ol Sr, Sp, Il Cb
B-71-72a	x				x		x	x	t				x			Af
B-71-121	x	x				x	x	x	x				x			
B-71-129	x	x					x	x	x	x			x			
B-71-190	x	x						x	x	x	x					
B-71-132	x			x				x		x						Hy
B-71-133	x			x				x		x						Il
B-71-136	x			x				x		x						Il
B-10-72	x				x											Tr, At
B-30-72	x	x					x	x	x	x			x			
B-52-72	x	x						x	x							Pt
B-94-72	x	x				x		x	x	x			x	x		
B-100-72	x						x	x	x							
B-103-72	x	x								x						Sl, Ol Hy, Opx
B-104-73	x	x								x						Hy, Op
B-105-73	x	x								x						Ol, Sr, Hy, Id
B-106-73	x	x						x		x						Id, Hy, Ol, Sl

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-118-72	x	x						x		x						Ox
B-122-72	x	x		x			x	x	x	x			x			Bi-Di, Ox
B-152-72	x	x					x	x	x	x				x		Op, Sc
B-181-72	x	x	x	x			x	x	x				x			
B-209-72	x				x		x	x	x	x				x	x	
B-210-72								x	x	x						Opx, Cm, Ox
B-211-72								x		x						Am, Cb, Su, Hy
B-212-72	x						x		x	x						Cb
B-213-72b	x	x			x		x		x	x						Tm, Op
B-213-72e	x	x			x				x	x						Cm, Hy, Mt
B-220-72	x	x	x				x	30	x							Su, Op
B-221-72	x	x					t	30	x	x			x	x		Op
B-227-72	x	x					x	38	x				x			
B-254-72	x	x					x	x	x					x	x	
B-312-72		x		x				30	x	x			x			Op
B-316-72	x	x	x				x	22	x	x			x	x	x	
B-401-72	x	x						x	x	x				x	x	Op
B-498-73	x	x					x	x		x	x					
B-597-73	x						x	x	x			x				Op
B-610-73	x	x	x				x	x	x	x			x	x	x	
B-611-73	x	x						x	x	x				x	x	Op
B-654-73	x	x						x	x	x			x	x		Il, Pt?
B-664-73		x	t			x			x	x			x	x		Mt, Il
B-682-73	x						x	x	x	x			x	x	x	Gf

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-683-73	x						x	x	x	x	x	x			x	Py,Cp, Po,Mc,Gf
B-683-73a	x							x	x	x		x				He,Il
B-768-73	x	x			x	x		x	x	x						
GR-1	x	x			x		x	x	x				x			Sn
GR-2	x	x			x		x	x	x				x			Ox
TMG-13-73		x		x												Cb,At,Ch
TMG-15-73	x	x				x									x	Tc,At
TMG-25-73	x			x						x						Cb,Cm
TMG-29-73									x							Hy,Cm Ox,Cb
TMG-31-73									x	x						Mt,Cm,Am
TMG-32-73	x			x	x				x	x						Tr?
TMG-33-73	Ph								x							Mt,Cm
TMG-34-73				?					x							Gu,Am,Cb Cm,Sl?
TMG-35-73				x					x	x						Mt,Cp,Cm
GF-7-73	x	x					x	x	x	x			x			
GF-11-73	x	x						x	x	x						Op

PYRRHOTITE GNEISS

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
2	Ph			x	x	x	x	x	x			x	x			
B-71-88	Ph				x	x	x	x	x							Gr,Tm,Rt
B-71-91						Mg	x		x			x	x	x		Py,Tm
B-71-96		t					?	?	x			x				Tr
B-71-104		t		x		x	x	x	x				x			Su,Gr,Tm
B-71-131						x	x	x	x			x	x			Gr,Po,He Py,Cp
B-62-72	Ph			x	x			x	x				x			Ox,Su
B-80-72		t		x	x			x	x				x			Su
B-134-72	x	x					x	x		x						Op
B-142-72		x		x				x	x	x						Sc,Hy
B-177-72	x	x								x						Cm,At
B-185-72	Ph						x	x	x				x	x		Gf,Su
B-196-72						Mg			x			?				Su,Cb,As
B-261-72	Ph						x		x			x				Su,Gf Cb,Rt
B-282-72	Ph				x		x		x						x	Su,Rt,Gf
B-283-72	Ph	t					x		x				x			Su
B-343-73	x				x		x	x	x						x	Tm,Gf Py,He
B-344-73	x						x	x	x							Tm,Py,Rt, He,Gf,Cp
B-345-73	x			x	x				x							Tm,Py,He
B-346-73	x						x	x	x			x		x	x	Tm,Gf, He,Py
B-348-73							x	x	x	x		x				Gf,Il, He,Cp,Po

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-349-73	x						x	x	x			x		x		Py, Po, Cp, He, Gf, Sc, Mc
B-352-73	Ph	t		x	x		x	x	x				x			Sc, Mc, Py, Po, He, Cp
B-353-73	Ph	t		x	x		x		x				x	x		Tm, He, Gf, Py, Po
B-355-73	x						x	x	x			x		x		Tm, Mc, Gf, Po
B-359-73	x				x		x	x	x							Tm, Po, Gf, He
B-363-73	x						x	x	x			x				Tm, Po, He, Py
B-364-73	x						x	x	x							He

PELITIC ROCKS

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
3	x								x	Al		x				Tm
B-71-16	x							x	x	x		x				Mt, Il
B-71-44	x						x	x	x	x	x	x				Qp
B-71-84	x							x	x	x	x	x				Gf
B-71-85	x								x	x	x	x				
B-71-97	x								x		x	x				Gr, He
B-71-109	x							x	x	x	x	x				Tm, Gf
B-34-72	x								x	x		x				
B-63-72	x								x	x	x	x				Tm
B-271-72	x							x		x		x				Ox
B-351-73	x								x	x	x	x				Tm, Il, Gf, Po, Py
B-358-73	x								x	x	x	x				Tm, Il, Gf, Py
B-365-73	x								x	x	x	x				Tm, Gf He
B-378-73	x							x	x		x	x				Op
B-379-73	x							x	x		x	x				
B-461-73	x							x	x	x	x	x				
B-484-73							x	x	x	x	x	x				
B-500-73	x						x	x	x		x	x			x	Op
B-686-73	x								x	x	x	x			x	
TMG-17-73	x							x		x		x				Gf, He
TMG-21-73	x							x	x	x	x			x		He
TMG-22-73	x						x	x	x	x		rr?			x	Po, Py, Cp

PSAMMITIC ROCKS

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-71-13	x							x	x			x	x			Op
B-71-14							x		x			x				Il, Mt
B-71-19	x							x	x	x		x				He, Il
B-71-43	x						x	x	x			x				
B-71-52a	x							x	x	x	x	x				Op
B-71-79	x						x	x	x			x				Op
B-71-81							x	x	x			x				Op
B-53-72	x						x	x	x			x				
B-239-72							x		x	x		x		x		Ox
B-307-72									x			x				
B-379-73	x							x	x		x	x	x	x		Mt, Il
B-382-73	x						x	x	x			x			x	
B-388-73	x						x	x	x	x	x	x	x			Op
B-390-73	x					x	x	x	x		x	x			x	
B-392-73	x						x	x	x		x	x				Op
B-395-73	x						t	x	x		x	x				
B-399-73	x						x	x	x			x			x	Op
B-405-73							x		x		x	x				Op
B-407-73	x		x				x	x	x	x						
B-411-73	x						x	x	x			x			x	
B-417-73	x						x	x	x	x	x	x				
B-442-73	x					x	x	x	x	x	x	x			x	Op
B-445-73	x						x	x	x			x		x	x	Op
B-453-73	x						x	x	x			x				

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-491-73	x						x	x	x	x	x	x				Op
B-500-73	x						x	x	x		x	x	x	x		Mt
B-505-73	x						x	x	x	x		x				Op
B-508-73	x						x	x	x			x				Op
B-556-73	x						x					x		x		Op
TMG-27-73	x						x	x	x							Tm, Gf

BIOTITE GNEISS

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-71-45		x						x	x	x					x	Op
B-71-66	x	x					x	x	x							Op
B-71-68	x							x	x	x			x			Op
B-59-72	x	x	x		x		x		x							
B-84-72	x	x	x		x		x	25 38	x						x	x
B-89-72		x				x		28	x				x	x		Op
B-126-72	x		x				x	25	x				x	x	x	Op
B-167-73	x	x				x	x	32	x				x	x		
B-236-72	x				x		x	22	x			x	x	x		
B-255-72	x	x	x				x	x					x	x	x	
B-260-72	x		x			x	x	25 55								x
B-262-72	x	x					x	30	x				x	x	x	Op
B-273-72	x	x						25 50	x	x					x	x
B-373-72	x				x			x	x	x		x				Op

MARBLES

Number	Bi	Hb	Ep	Di	Cc	Ch	Kf	Pf	Qz	Gt	Ky	Mv	Sp	Ap	Zr	Other
B-205-72				x			?		x			x				
B-208-72	Ph	t							x							Cb
B-213-72f	Ph	t			x											Do
B-213-72h		t			x											Do
B-213-72i	x	t							x							Cb
B-250-72a		t														Sr, Cb, Ox
B-252-72b																Sr, Cb
B-350-73	x	t							x	x						Cb, Mc, Gf, He, Py, Po, Cp
B-357-73	Ph	t							x							Cb, Gf, Po, He
TMG-25-73	x		x													Cb, Cm
TMG-26-73	x	t													x	Cb, Op

Appendix II Invariant Points in the system $\text{CaO} - \text{MgO} - \text{KAlSi}_3\text{O}_8 -$
 $\text{Al}_2\text{O}_3 - \text{SiO}_2 - \text{CO}_2 - \text{H}_2\text{O}.$

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
1	(Mv, Ch, Tr, Zo)	(Ph)	28
		(Kf)	28
		(Di)	28
		(Cc)	38
		(An)	44
		(Ky)	44
2	(Mv, Ch, Di, Zo)	(Ph)	28
		(Kf)	28
		(Tr)	28
		(Cc)	39
		(An)	1
		(Ky)	1
3	(Mv, Ch, Cc, Zo)	(Ph)	24
		(Kf)	24
		(Di)	39
		(Tr)	38
		(An)	75
		(Ky)	75
4	(Mv, Ch, An, Zo)	(Ph)	2
		(Kf)	2
		(Di)	1
		(Tr)	44
		(Cc)	75
5	(Mv, Ch, Ky, Zo)	(Ph)	2
		(Kf)	2
		(Di)	2
		(Tr)	2
		(Cc)	2
		(An)	2
6	(Mv, Tr, Di, Zo)	(Ph)	28
		(Kf)	28
		(Ch)	28
		(An)	54
		(Cc)	54
		(Ky)	52

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
7	(Mv, Tr, Cc, Zo)	(Ph)	14
		(Kf)	14
		(Ch)	38
		(Di)	54
		(An)	47
		(Ky)	47
8	(Mv, Tr, An, Zo)	(Ph)	18
		(Kf)	18
		(Ch)	44
		(Di)	54
		(Cc)	54
		(Ky)	44
9	(Mv, Tr, Ky, Zo)	(Ph)	17
		(Kf)	17
		(Ch)	44
		(Di)	52
		(Cc)	47
		(An)	44
10	(Mv, Di, Cc, Zo)	(Ph)	15
		(Kf)	15
		(Ch)	39
		(Tr)	54
		(An)	54
		(Ky)	49
11	(Mv, Di, An, Zo)	(Ph)	21
		(Kf)	21
		(Ch)	1
		(Tr)	54
		(Cc)	54
		(Ky)	1
12	(Mv, Di, Ky, Zo)	(Ph)	20
		(Kf)	20
		(Ch)	1
		(Tr)	52
		(Cc)	49
		(An)	1
13	(Mv, Cc, An, Zo)	(Ph)	9
		(Kf)	9
		(Ch)	75
		(Di)	54
		(Tr)	54
		(Ky)	75

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
14	(Mv, Cc, Ky, Zo)	(Ph)	8
		(Kf)	8
		(Ch)	75
		(Di)	49
		(Tr)	47
		(An)	75
15	(Mv, An, Ky, Zo, Ch)	(Ph)	2
		(Kf)	2
		(Di)	1
		(Tr)	44
		(Cc)	75
16	(Kf, Ch, Tr, Zo)	(Ph)	28
		(Mv)	28
		(Di)	28
		(Cc)	76
		(An)	42
		(Ky)	40
17	(Kf, Ch, Di, Zo)	(Ph)	28
		(Mv)	28
		(Tr)	28
		(Cc)	70
		(An)	43
		(Ky)	41
18	(Kf, Ch, Cc, Zo)	(Ph)	24
		(Mv)	24
		(Di)	70
		(Tr)	76
		(An)	66
		(Ky)	74
19	(Kf, Ch, An, Zo)	(Ph)	2
		(Mv)	2
		(Di)	43
		(Tr)	42
		(Cc)	66
		(Ky)	2
20	(Kf, Ch, Ky, Zo)	(Ph)	2
		(Mv)	2
		(Di)	41
		(Tr)	40
		(Cc)	74
		(An)	2

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
21	(Kf, Tr, Di, Zo)	(Ph)	28
		(Mv)	28
		(Ch)	28
		(Cc)	6
		(An)	6
		(Ky)	60
22	(Kf, Tr, Cc, Zo)	(Ph)	14
		(Mv)	14
		(Ch)	76
		(Di)	6
		(An)	6
		(Ky)	56
23	(Kf, Tr, An, Zo)	(Ph)	18
		(Mv)	18
		(Ch)	42
		(Di)	6
		(Cc)	6
		(Ky)	30
24	(Kf, Tr, Ky, Zo)	(Ph)	17
		(Mv)	17
		(Ch)	40
		(Di)	60
		(Cc)	56
		(An)	30
25	(Kf, Di, Cc, Zo)	(Ph)	15
		(Mv)	15
		(Ch)	70
		(Tr)	6
		(An)	6
		(Ky)	57
26	(Kf, Di, An, Zo)	(Ph)	21
		(Mv)	21
		(Ch)	43
		(Tr)	6
		(Cc)	6
		(Ky)	31
27	(Kf, Di, Ky, Zo)	(Ph)	20
		(Mv)	20
		(Ch)	41
		(Tr)	60
		(Cc)	57
		(An)	31

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
28	(Kf, Cc, An, Zo)	(Ph)	9
		(Mv)	9
		(Ch)	66
		(Tr)	6
		(Di)	6
		(Ky)	29
29	(Kf, Cc, Ky, Zo)	(Ph)	8
		(Mv)	8
		(Ch)	74
		(Tr)	56
		(Di)	57
		(An)	29
30	(Kf, An, Ky, Zo)	(Ph)	2
		(Mv)	2
		(Ch)	2
		(Tr)	30
		(Di)	31
		(Cc)	29
31	(Ph, Ch, Tr, Di, Zo)	(Mv)	28
		(Kf)	28
		(Cc)	3
		(An)	3
		(Ky)	4
32	(Ch, Tr, Cc, Zo)	(Ph)	3
		(Kf)	76
		(Mv)	38
		(Di)	3
		(An)	3
		(Ky)	63
33	(Ch, Tr, An, Zo)	(Ph)	3
		(Kf)	42
		(Mv)	44
		(Di)	3
		(Cc)	3
		(Ky)	44
34	(Ch, Tr, Ky, Zo)	(Ph)	4
		(Kf)	40
		(Mv)	44
		(Di)	4
		(Cc)	63
		(An)	44

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
35	(Ch, Di, Cc, Zo)	(Ph)	3
		(Kf)	70
		(Mv)	39
		(Tr)	3
		(An)	3
		(Ky)	64
36	(Ch, Di, An, Zo)	(Ph)	3
		(Mv)	1
		(Kf)	43
		(Tr)	3
		(Cc)	3
		(Ky)	1
37	(Ch, Di, Ky, Zo)	(Ph)	4
		(Mv)	1
		(Kf)	41
		(Tr)	4
		(Cc)	64
		(An)	1
38	(Ch, Cc, An, Zo)	(Ph)	3
		(Kf)	66
		(Mv)	75
		(Di)	3
		(Tr)	3
		(Ky)	75
39	(Ch, Cc, Ky, Zo)	(Ph)	
		(Mv)	75
		(Kf)	74
		(Di)	64
		(Tr)	63
		(An)	75
40	(Ch, An, Ky, Zo)	(Ph)	2
		(Mv)	1
			2
			44
			75
		(Kf)	2
		(Di)	1
		(Tr)	44
		(Cc)	75
41	(Tr, Di, Cc, Zo, An)	(Ph)	3
		(Mv)	54
		(Kf)	6
		(Cc)	3

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
42	(Tr, Di, An, Zo, Cc)	(Ph) (Mv) (Kf) (Ch) (Ky)	3 54 6 3 45
43	(Tr, Di, Ky, Zo)	(Ph) (Mv) (Kf) (Ch) (Cc) (An)	4 52 60 4 45 45
44	(Tr, Cc, An, Zo, Di)	(Ph) (Mv) (Kf) (Ch) (Ky)	3 54 6 3 45
45	(Tr, Cc, Ky, Zo)	(Ph) (Kf) (Mv) (Ch) (Di) (An)	56 47 63 45 77 45
46	(Tr, An, Ky, Zo)	(Ph) (Kf) (Mv) (Ch) (Di) (Cc)	30 44 44 45 45
47	(Di, Cc, An, Zo, Tr)	(Ph) (Kf) (Mv) (Ch) (Ky)	3 6 54 3 45
48	(Di, Cc, Ky, Zo)	(Ph) (Mv) (Kf) (Ch) (Tr) (An)	49 57 64 45 45

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
49	(Di, An, Ky, Zo)	(Ph) (Kf) (Mv) (Ch) (Tr) (Cc)	31 1 1 45 45
50	(Cc, An, Ky, Zo)	(Ph) (Kf) (Mv) (Ch) (Di) (Tr)	29 75 75 45 45
51	(Ph, Mv, Kf, Ch, Zo)	(Tr) (Di) (An) (Cc) (Ky)	28 28 2 24 2
52	(Ph, Mv, Kf, Di, Zo)	(Ch) (Tr) (An) (Cc) (Ky)	28 28 21 15 20
53	(Ph, Kf, Mv, Ch, Tr, Di)	(An) (Cc) (Ky) (Zo)	27 25 26 28
54	(Mv, Ch, Tr, Cc)	(Ph) (Kf) (Di) (An) (Ky) (Zo)	25 25 25 34 32 38
55	(Mv, Ch, Tr, An)	(Ph) (Kf) (Cc) (Ky) (Zo) (Di)	27 27 33 44 44 27
56	(Mv, Ch, Tr, Ky)	(Ph) (Kf) (Di) (An) (Cc) (Zo)	26 26 26 44 32 44

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
57	(Mv, Ch, Di, Cc)	(Ph)	25
		(Kf)	25
		(Tr)	25
		(An)	35
		(Ky)	34
		(Zo)	39
58	(Mv, Ch, Di, An)	(Ph)	27
		(Kf)	27
		(Tr)	27
		(Cc)	35
		(Ky)	1
		(Zo)	1
59	(Mv, Ch, Di, Ky)	(Ph)	26
		(Kf)	26
		(Tr)	26
		(An)	1
		(Cc)	34
		(Zo)	1
60	(Mv, Ch, Cc, An)	(Ph)	22
		(Kf)	22
		(Tr)	33
		(Di)	35
		(Ky)	75
		(Zo)	75
61	(Mv, Ch, Cc, Ky)	(Ph)	23
		(Kf)	23
		(Tr)	32
		(Di)	34
		(An)	75
		(Zo)	75
62	(Mv, Ch, An, Ky, Zo)	(Ph)	2
		(Kf)	2
		(Tr)	44
		(Di)	1
		(Cc)	75
63	(Mv, Tr, Di, Cc)	(Ph)	25
		(Kf)	25
		(Ch)	25
		(An)	54
		(Ky)	50
		(Zo)	54

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
64	(Mv, Tr, Di, An)	(Ph) (Kf) (Ch) (Cc) (Ky) (Zo)	27 27 27 54 51 54
65	(Mv, Tr, Di, Ky)	(Ph) (Kf) (Ch) (An) (Cc) (Zo)	26 26 26 51 50 52
66	(Mv, Tr, Cc, An)	(Ph) (Kf) (Ch) (Di) (Ky) (Zo)	11 11 33 54 46 54
67	(Mv, Tr, Cc, Ky)	(Ph) (Kf) (Ch) (Di) (An) (Zo)	10 10 32 35 46 47
68	(Mv, Tr, An, Ky)	(Ph) (Kf) (Ch) (Di) (Cc) (Zo)	16 16 44 51 46 44
69	(Mv, Di, Cc, An)	(Ph) (kf) (Ch) (Tr) (Ky) (Zo)	13 13 35 54 48 54
70	(Mv, Di, Cc, Ky)	(Ph) (Kf) (Ch) (Tr) (An) (Zo)	12 12 34 50 48 49

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
71	(Mv, Di, An, Ky)	(Ph)	19
		(Kf)	19
		(Ch)	1
		(Tr)	51
		(Cc)	48
		(Zo)	1
72	(Mv, Cc, An, Ky)	(Ph)	7
		(Kf)	7
		(Ch)	75
		(Tr)	46
		(Di)	48
		(Zo)	75
73	(Ph, Mv, Kf, Ch, Tr, Di)	(An)	27
		(Cc)	25
		(Ky)	26
		(Zo)	28
74	(Kf, Ch, Tr, Cc)	(Ph)	25
		(Mv)	25
		(Di)	25
		(An)	73
		(Ky)	36
		(Zo)	76
75	(Kf, Ch, Tr, An)	(Ph)	27
		(Mv)	27
		(Di)	27
		(Ky)	37
		(Cc)	73
		(Zo)	42
76	(Kf, Ch, Tr, Ky)	(Ph)	26
		(Mv)	26
		(Di)	26
		(An)	37
		(Cc)	36
		(Zo)	40
77	(Kf, Ch, Di, Cc)	(Ph)	25
		(Mv)	25
		(Tr)	25
		(An)	68
		(Ky)	67
		(Zo)	70

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
78	(Kf, Ch, Di, An)	(Ph)	27
		(Mv)	27
		(Tr)	27
		(Cc)	68
		(Ky)	71
		(Zo)	43
79	(Kf, Ch, Di, Ky)	(Ph)	26
		(Mv)	26
		(Tr)	26
		(An)	71
		(Cc)	67
		(Zo)	41
80	(Kf, Ch, Cc, An)	(Ph)	22
		(Mv)	22
		(Tr)	73
		(Di)	68
		(Ky)	69
		(Zo)	66
81	(Kf, Ch, Cc, Ky)	(Ph)	23
		(Mv)	23
		(Tr)	36
		(Di)	67
		(An)	69
		(Zo)	74
82	(Kf, Ch, An, Ky)	(Ph)	2
		(Mv)	2
		(Tr)	37
		(Di)	71
		(Cc)	69
		(Zo)	2
83	(Kf, Tr, Di, Cc)	(Ph)	25
		(Mv)	25
		(Ch)	25
		(An)	6
		(Ky)	58
		(Zo)	6
84	(Kf, Tr, Di, An)	(Ph)	27
		(Mv)	27
		(Ch)	27
		(Ky)	59
		(Cc)	6
		(Zo)	6

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
85	(Kf, Tr, Di, Ky)	(Ph) (Mv) (Ch) (An) (Cc) (Zo)	26 26 26 59 58 60
86	(Kf, Tr, Cc, An)	(Ph) (Mv) (Ch) (Di) (Ky) (Zo)	11 11 73 6 55 6
87	(Kf, Tr, Cc, Ky)	(Ph) (Mv) (Ch) (Di) (An) (Zo)	10 10 36 58 55 56
88	(Kf, Tr, An, Ky)	(Ph) (Mv) (Ch) (Di) (Cc) (Zo)	16 16 37 59 55 30
89	(Kf, Di, Cc, An)	(Ph) (Mv) (Ch) (Tr) (Ky) (Zo)	13 13 68 6 65 6
90	(Kf, Di, Cc, Ky)	(Ph) (Mv) (Ch) (Tr) (An) (Zo)	12 12 67 58 65 57
91	(Kf, Di, An, Ky)	(Ph) (Mv) (Ch) (Tr) (Cc) (Zo)	19 19 71 59 65 31

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
92	(Kf, Cc, An, Ky)	(Ph)	7
		(Mv)	7
		(Ch)	69
		(Tr)	55
		(Di)	65
		(Zo)	29
93	(Ch, Tr, Di, Cc)	(Ph)	25
			3
			5
		(Mv)	25
		(Kf)	25
		(An)	3
		(Ky)	5
		(Zo)	3
94	(Ph, Ch, Tr, Di, An)	(Mv)	27
		(Kf)	27
		(Cc)	3
		(Ky)	72
		(Zo)	3
95	(Ph, Ch, Tr, Di, Ky)	(Kf)	26
		(Mv)	26
		(Cc)	5
		(An)	72
		(Zo)	4
96	(Ch, Tr, Cc, An)	(Ph)	3
		(Kf)	73
		(Mv)	33
		(Di)	3
		(Ky)	62
		(Zo)	3
97	(Ch, Tr, Cc, Ky)	(Ph)	5
		(Kf)	36
		(Mv)	32
		(Di)	5
		(An)	62
		(Zo)	63
98	(Ch, Tr, An, Ky)	(Ph)	72
		(Mv)	44
		(Kf)	37
		(Di)	72
		(Cc)	62
		(Zo)	44

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
99	(Ch, Di, Cc, An)	(Ph)	3
		(Mv)	35
		(Kf)	68
		(Tr)	3
		(Ky)	61
		(Zo)	3
100	(Ch, Di, Cc, Ky)	(Ph)	5
		(Kf)	67
		(Mv)	34
		(Tr)	5
		(An)	61
		(Zo)	64
101	(Ch, Di, An, Ky)	(Ph)	72
		(Kf)	71
		(Mv)	1
		(Tr)	72
		(Cc)	61
		(Zo)	1
102	(Ch, Cc, An, Ky)	(Ph)	
		(Kf)	69
		(Mv)	75
		(Di)	61
		(Tr)	62
		(Zo)	75
103	(Tr, Di, Cc, An)	(Ph)	25
			3
		(Kf)	25
		(Mv)	25
			54
		(Ch)	3
		(Ky)	3
		(Zo)	77
			54
			3
104	(Tr, Di, Cc, Ky)	(Ph)	5
		(Mv)	50
		(Kf)	58
		(Ch)	5
		(An)	45
		(Zo)	45

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
105	(Tr, Di, An, Ky)	(Ph)	72
		(Mv)	51
		(Kf)	59
		(Ch)	72
		(Cc)	45
		(Zo)	45
106	(Tr, Cc, An, Ky)	(Ph)	
		(Mv)	46
		(Kf)	55
		(Ch)	62
		(Di)	45
		(Zo)	45
107	(Di, Cc, An, Ky)	(Ph)	
		(Mv)	48
		(Kf)	65
		(Ch)	61
		(Tr)	45
		(Zo)	45
108	(Ph, Mv, Kf, Di, An)	(Cc)	13
		(Ky)	19
		(Tr)	27
		(Ch)	27
		(Zo)	21
109	(Ph, Mv, Kf, Di, Ky)	(Ch)	26
		(Zo)	20
		(Cc)	12
		(Tr)	26
		(An)	19
110	(Ph, Ch, Tr, Di, An)	(Mv)	27
		(Kf)	27
		(Ky)	72
		(Cc)	3
		(Zo)	3
111	(Ph, Mv, Kf, Di, Cc)	(Ch)	25
		(Tr)	25
		(An)	13
		(Zo)	15
		(Ky)	12
112	(Ph, Ch, Tr, Di, Cc)	(Mv)	25
		(Kf)	25
		(An)	3
		(Ky)	5
		(Zo)	3

<u>Invariant Point Number</u>	<u>Notation</u>	<u>Reaction Notation</u>	<u>Reaction Number</u>
113	(Ph, Ch, Tr, Di, Ky)	(Mv)	26
		(Kf)	26
		(Cc)	5
		(Zo)	4
		(An)	72
114	(Ph, Mv, Kf, Ky, Zo)	(Ch)	2
		(Tr)	17
		(Di)	20
		(Cc)	8
		(An)	2
115	(Ph, Mv, Kf, An, Zo)	(Ch)	2
		(Tr)	18
		(Di)	21
		(Cc)	9
		(Ky)	2
116	(Ph, Mv, Kf, Ch, Ky)	(Tr)	26
		(Di)	26
		(Cc)	23
		(An)	2
		(Zo)	2
117	(Ph, Mv, Kf, An, Ky)	(Ch)	2
		(Tr)	16
		(Di)	19
		(Cc)	7
		(Zo)	2
118	(Ph, Kf, Mv, Ch, An)	(Tr)	27
		(Di)	27
		(Cc)	22
		(Zo)	2
		(Ky)	2
119	(Ph, Kf, Mv, Ch, Zo)	(Tr)	28
		(Di)	28
		(Ky)	2
		(Cc)	24
		(An)	2
120	(Ph, Ch, Tr, Di, Zo)	(Mv)	28
		(Kf)	28
		(An)	3
		(Ky)	4
		(Cc)	3

Appendix III Computer program PROCAL.

This program calculates the values of X , A , and L for the KAL projection from mineral analysis

```

1.000 C PROGRAM TO CALCULATE K.A.L. PROJECTION,
2.000 C R MOORE FEB. 3, 1976
3.000 C
4.000     IMPLICIT DOUBLE PRECISION (A-H,O-Z)
5.000     DIMENSION X(6,6),A(10, 6),B(6,6)
6.000     PRINT 10
7.000 10 FORMAT (6X,'PROJECTION MATRIX',//)
8.000     DO 2 I = 1,6
9.000     READ 3,(X(I,J),J = 1,6)
10.000    PRINT 3,(X(I,J),J=1,6)
11.000 2 CONTINUE
12.000 3 FORMAT (10G,0)
13.000 9 FORMAT (5X,6F10.3)
14.000     CALL INVERT(X,6,6,DET,TEST)
15.000     PRINT 12,(TEST)
16.000 12 FORMAT (//,3X,'TEST = ',14,6X,'IF TEST=0,THE SOLUTIONS ARE VALID')
17.000     DO 4 I = 1,6
18.000     DO 4 J = 1,6
19.000     B(I,J) = X(I,J)
20.000 4 CONTINUE
21.000     PRINT 14
22.000 14 FORMAT (1H1,5X,' MINERAL MATRIX',//)
23.000     DO 5 I = 1,10
24.000     READ 3,(A(I,J),J = 1,6)
25.000     PRINT 9,(A(I,J),J = 1,6)
26.000 5 CONTINUE
27.000     PRINT 6
28.000 6 FORMAT (1H1,5X,' K.A.L. PROJECTION MATRIX',//)
29.000     CALL MATMP (A,B,10,6,6,1)
30.000     DO 7 I = 1,10
31.000     PRINT 9,(A(I,J),J = 1,6)
32.000 7 CONTINUE
33.000     CALL EXIT
34.000     END

```

Appendix IV Computer program COMBAL.

This program finds and balances all the possible reactions among the phases entered into the program.

```

1.000 C      THIS PART OF PROGRAM COMBINES MINERALS IN ALL POSSIBLE COMBINATIONS
2.000 C
3.000      DIMENSION CMAT(25,12),RMAT(25,12),CMAT(25,12),NAME(25),NAM(25),
4.000      NAME(25),ICOPY(25),ICRO(25),LABEL(25),NUMERAL(1001)
5.000      COMMON CMAT,NMAX,NAX,PBX,NAMD,NUMERAL
6.000      READ 290, (NUMERAL(I),I = 1,999)
7.000 290 FORMAT (20A1)
8.000      READ 300,ICOMP,MINERAL
9.000      READ 310,(LABEL(I),I = 1,20)
10.000     PRINT 320,(LABEL(I),I = 1,20)
11.000     PRINT 320
12.000     DO 18 I = 1,MINERAL
13.000     READ 330,NAME(I),(RMAT(I,J),J = 1,ICOMP)
14.000     PRINT 340,NAME(I),(RMAT(I,J),J = 1,ICOMP)
15.000 18 CONTINUE
16.000     PRINT 320
17.000 300 FORMAT (2G,0)
18.000 310 FORMAT (20A1)
19.000 320 FORMAT (10X,20A1)
20.000 330 FORMAT (A1,10G,0)
21.000 340 FORMAT (5X,A1,7(2X,F4,1))
22.000     NMAX = ICOMP + 1
23.000     KRN = 0
24.000     MINERAL = NMAX - 2
25.000     NUTMIN = 2
26.000     DO 3000 I = 1,MINERAL
27.000     NUTMIN = NUTMIN + 1
28.000     IF (NUTMIN.GT.11) GO TO 6000
29.000     NUMA = MINERAL - NUTMIN + 1
30.000     IF (NUMA.LT.1) GO TO 6000
31.000     IF (NUMA.GE.MINERAL) GO TO 6000
32.000     NUMA1 = NUMA + 1
33.000     IF (NUMA1.GT.MINERAL) GO TO 360
34.000     NUMA2 = NUMA1 + 1
35.000     IF (NUMA2.GT.MINERAL) GO TO 361
36.000     NUMA3 = NUMA2 + 1
37.000     IF (NUMA3.GT.MINERAL) GO TO 362
38.000     NUMA4 = NUMA3 + 1
39.000     IF (NUMA4.GT.MINERAL) GO TO 363
40.000     NUMA5 = NUMA4 + 1
41.000     IF (NUMA5.GT.MINERAL) GO TO 364
42.000     NUMA6 = NUMA5 + 1
43.000     IF (NUMA6.GT.MINERAL) GO TO 365
44.000     NUMA7 = NUMA6 + 1
45.000     IF (NUMA7.GT.MINERAL) GO TO 366
46.000     NUMA8 = NUMA7 + 1
47.000     IF (NUMA8.GT.MINERAL) GO TO 367
48.000     NUMA9 = NUMA8 + 1
49.000     IF (NUMA9.GT.MINERAL) GO TO 368
50.000     NUMA10 = NUMA9 + 1
51.000     IF (NUMA10.GT.MINERAL) GO TO 369
52.000     GO TO 370
53.000 360 NUMA1 = MINERAL
54.000 361 NUMA2 = MINERAL
55.000 362 NUMA3 = MINERAL
56.000 363 NUMA4 = MINERAL
57.000 364 NUMA5 = MINERAL
58.000 365 NUMA6 = MINERAL
59.000 366 NUMA7 = MINERAL
60.000 367 NUMA8 = MINERAL
61.000 368 NUMA9 = MINERAL
62.000 369 NUMA10 = MINERAL
63.000 370 DO 4000 I1 = 1,NUMA
64.000     KAT = 1
65.000     ICOPY(1) = I1
66.000     J2 = I1 + 1
67.000     DO 4001 I2 = J2,NUMA1
68.000     KAT = 2
69.000     ICOPY(2) = I2
70.000     J3 = I2 + 1

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71.000 DO 4002 I3 = J3,NUMA2
72.000 KAT = 3
73.000 ICOPY(3) = I3
74.000 IF(NUMMIN.EQ.3) GO TO 4115
75.000 J4 = I3 + 1
76.000 DO 4003 I4 = J4,NUMA3
77.000 KAT = 4
78.000 ICOPY(4) = I4
79.000 IF(NUMMIN.EQ.4) GO TO 4115
80.000 J5 = I4 + 1
81.000 DO 4004 I5 = J5,NUMA4
82.000 KAT = 5
83.000 ICOPY(5) = I5
84.000 IF(NUMMIN.EQ.5) GO TO 4115
85.000 J6 = I5 + 1
86.000 DO 4005 I6 = J6,NUMA5
87.000 KAT = 6
88.000 ICOPY(6) = I6
89.000 IF(NUMMIN.EQ.6) GO TO 4115
90.000 J7 = I6 + 1
91.000 DO 4006 I7 = J7,NUMA6
92.000 KAT = 7
93.000 ICOPY(7) = I7
94.000 IF(NUMMIN.EQ.7) GO TO 4115
95.000 J8 = I7 + 1
96.000 DO 4007 I8 = J8,NUMA7
97.000 KAT = 8
98.000 ICOPY(8) = I8
99.000 IF(NUMMIN.EQ.8) GO TO 4115
100.000 J9 = I8 + 1
101.000 DO 4008 I9 = J9,NUMA8
102.000 KAT = 9
103.000 ICOPY(9) = I9
104.000 IF(NUMMIN.EQ.9) GO TO 4115
105.000 J10 = I9 + 1
106.000 DO 4009 I10 = J10,NUMA9
107.000 KAT = 10
108.000 ICOPY(10) = I10
109.000 IF(NUMMIN.EQ.10) GO TO 4115
110.000 J11 = I10 + 1
111.000 DO 4010 I11 = J11,NUMA10
112.000 KAT = 11
113.000 ICOPY(11) = I11
114.000 4115 DO 5110 J = 1,NUMMIN
115.000 HCOPY = ICOPY(J)
116.000 DO 5120 K = 1,ICOMP
117.000 CCMAT(J,K) = RCMAT(HCOPY,K)
118.000 5120 CONTINUE
119.000 NAME(J) = NAME(HCOPY)
120.000 5110 CONTINUE
121.000 C
122.000 C THIS PART OF THE PROGRAM REDUCES THE PRECEDING MATRIX TO A
123.000 " SQUARE MATRIX IF POSSIBLE.
124.000 C
125.000 MAX = ICOMP
126.000 DO 380 I = 1,ICOMP
127.000 IZERO(I) = 0
128.000 380 CONTINUE
129.000 ICOPY = 0
130.000 IF (NUMMIN-ICOMP) 159,159,1054
131.000 159 L = 0
132.000 DO 160 J = 1,ICOMP
133.000 NUMBER = 0
134.000 DO 161 I = 1,NUMMIN
135.000 IF(ABS(CCMAT(I,J)).LT.0.0001) GO TO 161
136.000 GO TO 160
137.000 161 CONTINUE
138.000 L = L + 1
139.000 IZERO(L) = J
140.000 160 CONTINUE
141.000 NL = L
142.000 NRES = NUMMIN - 1
143.000 NARS = ICOMP - NRES
144.000 IF(NARS-L) 3999,1050,3999
145.000 3999 GO TO (4000,4001,4002,4003,4004,4005,4006,4007,4008,4009,4010),KAT
146.000 1050 L = 1
147.000 IF (NL.EQ.0) GO TO 1054
148.000 DO 1070 J = 1,ICOMP
149.000 ICOPY = ICOPY + 1
150.000 IF(IZERO(L)-J) 1052,1054,1052

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151.000 1504 I = I + 1
152.000      ICPIY = ICPIY-1
153.000      GO TO 1070
154.000 1052 DO 1060 I = 1,NUMMIN
155.000      CCMAT(I,ICPIY) = CCMAT(I,J)
156.000 1060 CONTINUE
157.000 1070 CONTINUE
158.000      MAX = ICPIY
159.000      GO TO 1056
160.000 1054 DO 1061 I = 1,NUMMIN
161.000      DO 1061 J = 1,ICOMP
162.000      CCMAT(I,J) = CCMAT(I,J)
163.000 1061 CONTINUE
164.000      KRIC = NUMMIN - MAX
165.000      IF(KRIC-1) 4020,1056,4020
166.000 1056 CONTINUE
167.000 C
168.000 C      THIS PART OF THE PROGRAM TESTS TO SEE IF A BALANCED EQUATION
169.000 C      IS POSSIBLE
170.000 C
171.000      DO 150 J = 1,MAX
172.000      NUMBER = 0
173.000      DO 151 I = 1,NUMMIN
174.000      IF(ABS(CCMAT(I,J)).LT.0.0001) GO TO 151
175.000      NUMBER = NUMBER + 1
176.000      IF(NUMBER-2) 151,150,150
177.000 151 CONTINUE
178.000      IF(NUMBER.LT.2) GO TO 2020
179.000 150 CONTINUE
180.000      ISOLN = 1
181.000      GO TO 153
182.000 2020 ISOLN = 0.0
183.000 153 IF(ISOLN) 4020,4020,210
184.000 210 NMAX = NUMMIN
185.000      DO 250 I = 1,NMAX
186.000      NAME(I) = NAME(I)
187.000 250 CONTINUE
188.000      CALL BALANCE
189.000 4020 GO TO (4000,4001,4002,4003,4004,4005,4006,4007,4008,4009,4010),KAT
190.000 4010 CONTINUE
191.000 4009 CONTINUE
192.000 4008 CONTINUE
193.000 4007 CONTINUE
194.000 4006 CONTINUE
195.000 4005 CONTINUE
196.000 4004 CONTINUE
197.000 4003 CONTINUE
198.000 4002 CONTINUE
199.000 4001 CONTINUE
200.000 4000 CONTINUE
201.000 3000 CONTINUE
202.000      GO TO 6005
203.000 6000 PRINT 320
204.000      PRINT 6001
205.000 6001 FORMAT (3X,'DUE TO LIMITATIONS OF THIS PROGRAM NO MORE SOLUTIONS'
206.000      1 ARE POSSIBLE')
207.000 6005 CALL EXIT
208.000      END
209.000
210.000
211.000
212.000
213.000
214.000      SUBROUTINE BALANCE
215.000 C
216.000 C      PROGRAM TO BALANCE MINERALOGICAL EQUILIBRIA
217.000 C      IN OTHER WORDS MASS BALANCE EQUATIONS
218.000 C      ARITHMETIC APPROACH BY R MOORE
219.000 C      COMPUTER LOGIC SUPPLIED BY H YZLEDDRAAT
220.000 C      GULL WORK SUPPLIED BY R MOORE
221.000 C
222.000 C      EQUATIONS BALANCED BY MATRIX METHOD OF D.S.KORZHINSKII
223.000 C      DETERMINATES SOLVED BY GAUSS TRANSFORMATIONS
224.000 C
225.000      DIMENSION CCMAT(25,12),CCPMAT(25,12),NAME(25),NAME(25),MINERAL(12)
226.000      J,COEF(12),COEFF(12),KOLF(12),IALPAR(12),HUPAR(12),NUMERAL(1001)
227.000      I,C(25,12)
228.000      COMMON CCMAT,NMAX,MAX,KRN,NAME,MINERAL,CCPMAT,DET,NTRIES,C
229.000      DATA MINERAL/LHCD ,4HWA /
230.000      DATA EQUALS/5H = /

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231.000      LEAP = 0
232.000      JCD = 25
233.000      JWA = 25
234.000      KCOF(25) = 0
235.000      DO 4 I = 1,NMAX
236.000      NAME(I) = NAME(I)
237.000      KCOF(I) = 0
238.000      4 CONTINUE
239.000      DO 10 N = 1,NMAX
240.000      LEAP = LEAP + 1
241.000      ICOPY = 0
242.000      DO 7 I = 1,NMAX
243.000      ICOPY = ICOPY + 1
244.000      IF(I-LEAP) 6,5,6
245.000      5 I = I + 1
246.000      6 DO 7 J = 1,NMAX
247.000      CUMAT(ICOPY,J) = CUMAT(I,J)
248.000      7 CONTINUE
249.000      NTIES = 0
250.000      CALL GAUSS(N)
251.000      IF(ABS(DET).LT..0001) GO TO 9
252.000      8 ITEST = N/2
253.000      ITESTD = ITEST*2
254.000      IF(N.NE.ITESTD) GO TO 21
255.000      DET = -DET
256.000      21 IF(DET) 2,9,3
257.000      2 DET = DET*100. - .5
258.000      GO TO 9
259.000      3 DET = DET*100. + .5
260.000      9 KCOF(N) = DET
261.000      10 CONTINUE
262.000      DO 900 I = 1,2
263.000      NAM = MINERAL(I)
264.000      DO 500 J = 1,NMAX
265.000      IF (NAM.EQ.NAME(J)) GO TO 600
266.000      500 CONTINUE
267.000      GO TO 900
268.000      600 GO TO (700,800) I
269.000      700 JCD = J
270.000      GO TO 900
271.000      800 JWA = J
272.000      900 CONTINUE
273.000      950 IF(KCOF(JCD)) 1502,1500,1501
274.000      1500 IF (KCOF(JWA)) 1502,1504,1501
275.000      1501 KOR = -1
276.000      GO TO 1503
277.000      1502 KOR = 1
278.000      1503 DO 20 N = 1,NMAX
279.000      KCOF(N) = KCOF(N) + KOR
280.000      20 CONTINUE
281.000      1504 IPOS = 1
282.000      INEG = 7
283.000      DO 210 I = 1,NMAX
284.000      IF(KCOF(I)) 200,210,205
285.000      200 COEFF(I) = KCOF(I)/100
286.000      HUPAR(INEG) = COEFF(I)
287.000      HUP = -HUPAR(INEG)
288.000      HUPAR(INEG) = NUMERAL(HUP)
289.000      IALPAR(INEG) = NAME(I)
290.000      INEG = INEG + 1
291.000      GO TO 210
292.000      205 COEFF(I) = KCOF(I)/100
293.000      HUPAR(IPOS) = COEFF(I)
294.000      IALPAR(IPOS) = NAME(I)
295.000      HUP = HUPAR(IPOS)
296.000      HUPAR(IPOS) = NUMERAL(HUP)
297.000      IPOS = IPOS + 1
298.000      210 CONTINUE
299.000      IPOS = IPOS-1
300.000      INEG = INEG-1
301.000      KRN = KRN + 1
302.000      PRINT 222
303.000      222 FORMAT (2X,5A4)
304.000      PRINT 221,KRN, (HUPAR(I),IALPAR(I),I = 1,IPOS),EQUALS,(HUPAR(I),IA
305.000      LPAR(I),I = 7,INEG)
306.000      221 FORMAT (2X,'REACTION #',I4,3X,20(A4))
307.000      RETURN
308.000      END

```

```

314.000 SUBROUTINE GAMES(N)
315.000 DIMENSION CHMAT(25,12),A(25,12),SAV'AT(25,12),C(25,12),HAND(25)
316.000 1,IMPERIAL(1001)
317.000 COMMON CHMAT,IMAX,IMAX,KRM,HAND,IMPERIAL,A,DET,NTRIES,C
318.000 IMAX = MAX-1
319.000 104 DO 1 I = 1,IMAX
320.000 DO 1 J = 1,IMAX
321.000 SAV'AT(I,J) = A(I,J)
322.000 1 CONTINUE
323.000 IG = 1
324.000 DO 110 I = 1,IMAX
325.000 IG = IG + 1
326.000 IF (ABS(A(I,1)).LT.0.0001) GO TO 20
327.000 GO TO 105
328.000 80 NC = I + 1
329.000 DO 3 J = NC,IMAX
330.000 IF (ABS(A(I,J)).LT.0.0001) GO TO 3
331.000 DO 2 K = 1,IMAX
332.000 T = A(I,K)
333.000 A(I,K) = A(J,K)
334.000 A(J,K) = T
335.000 2 CONTINUE
336.000 GO TO 4
337.000 3 CONTINUE
338.000 4 NTRIES = NTRIES + 1
339.000 IF (NTRIES-20) 104,104,140
340.000 105 DO 109 K = IG,MAX
341.000 IF (ABS(A(K,1)).LT.0.00001) GO TO 109
342.000 106 FAC = A(K,1)/A(I,1)
343.000 A(K,1) = 0
344.000 DO 108 J = IG,IMAX
345.000 A(K,J) = A(K,J)-FAC*A(I,J)
346.000 108 CONTINUE
347.000 109 CONTINUE
348.000 110 CONTINUE
349.000 IF (ABS(A(IMAX,IMAX)).LT.0.00001) GO TO 140
350.000 DET = A(I,1)
351.000 DO 115 I = 2,IMAX
352.000 DET = DET*A(I,1)
353.000 115 CONTINUE
354.000 NTT = NTRIES/2
355.000 NTT = NTT+2
356.000 IF (NTRIES.EQ.NTT) GO TO 142
357.000 DET = -DET
358.000 GO TO 142
359.000 140 DET = 0.0
360.000 142 RETURN
361.000 END

```

368.000	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
369.000	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
370.000	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
371.000	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
372.000	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
373.000	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
374.000	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140
375.000	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160
376.000	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180
377.000	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200
378.000	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220
379.000	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240
380.000	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260
381.000	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280
382.000	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300
383.000	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320
384.000	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340
385.000	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360
386.000	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380
387.000	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400
388.000	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420
389.000	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440
390.000	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460
391.000	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480
392.000	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500
393.000	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520

394.000	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540
395.000	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560
396.000	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580
397.000	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600
398.000	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620
399.000	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640
400.000	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660
401.000	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680
402.000	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700
403.000	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720
404.000	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740
405.000	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760
406.000	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780
407.000	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800
408.000	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820
409.000	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840
410.000	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860
411.000	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880
412.000	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900
413.000	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920
414.000	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940
415.000	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960
416.000	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980
417.000	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	

Appendix V. Computer program HESAP.

This program calculates the standard enthalpy of reaction of the solids (298.1) from an experimental reaction

```

1.000 C   PROGRAM TO CALCULATE ENTHALPY OF SOLIDS FOR A REACTION AT S.T.P.
2.000 C   R MOORE , JUNE 1976
3.000 C .....
4.000     DIMENSION TITLE(10),COMP(10)
5.000     R = 1.98726
6.000     READ 100,NER
7.000     DO 90,I = 1,NER
8.000       READ 200,((TITLE(J),J=1,10),COMP,I,VAR)
9.000       PRINT 250,((TITLE(J),J=1,10)
10.000      READ 300,((COMP(J),J=1,10),S,V)
11.000      PRINT 350,((COMP(J),J=1,10)
12.000      READ 100,NEP
13.000      DO 85,K = 1,NEP
14.000        READ 400,KAT,P,TC,PWA,FCWA,PCD,FCCD
15.000        T = TC + 273.15
16.000        IF (PWA.LT.0.01) GO TO 50
17.000        IF (PCD.LT.0.01) GO TO 60
18.000        RLK = (VAR*DLOG(PWA*FCWA)) + (COMP*DLOG(PCD*FCCD))
19.000        GO TO 70
20.000  50 IF (PCD.LT.0.01) GO TO 65
21.000        RLK = COMP*DLOG(PCD*FCCD)
22.000        GO TO 70
23.000  60 IF (PWA.LT.0.01) GO TO 65
24.000        RLK = VAR*DLOG(PWA*FCWA)
25.000        GO TO 70
26.000  65 RLK = 0.0
27.000  70 GWA = -54742. + (3.7489*TC) - (7.1886E-5*TC*TC) + (1.2593*TC*DLOG(TC
28.000      1)) - (2097.3/TC)
29.000      GCD = -93994. - (1.0187*T) + ( .44600E-3*T*T) - (.61901E-7*T*T*T)
30.000      H = -R*T*RLK + T*S - V*(P-1) - VAR*GWA - COMP*GCD
31.000      PRINT 500,KAT,H,TC
32.000  85 CONTINUE
33.000  90 CONTINUE
34.000     100 FORMAT (G.0)
35.000     200 FORMAT (10A4,2G.0)
36.000     250 FORMAT (1H1,2A,10A4,/)
37.000     300 FORMAT (10A4,2G.0)
38.000     350 FORMAT (2X,10A4,/,/,10X,' ENTHALPY ',5X,' I OF EXPERIMENT '/')
39.000     400 FORMAT (A4,6G.0)
40.000     500 FORMAT (27,A4,4X,F10.2,8X,F6.2)
41.000     CALL EXIT
42.000     END

```

Appendix VI Computer program KCONS.

This program calculates the dependence of all reactions to the independent reactions.

```

1.000 C      PROGRAM TO CALCULATE DEPENDENCE OF REACTIONS ON INDEPENDENT REACTIONS
2.000 C      R MOORE OCTOBER 1975
3.000      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
4.000      DIMENSION X(13,13),A(74,13),B(13,6)
5.000      PRINT 10
6.000      DO 2 I = 1,13
7.000      READ 3,(X(I,J),J = 1,13)
8.000      PRINT 9,(X(I,J),J = 1,13)
9.000      2 CONTINUE
10.000      CALL INVERT (X,13,13,DEF,TEST)
11.000      PRINT 12,(TEST)
12.000      DO 4 I = 1,13
13.000      DO 4 J = 1,6
14.000      B(I,J) = X(I,J)
15.000      4 CONTINUE
16.000      PRINT 14
17.000      DO 5 I = 1,74
18.000      READ 3,(A(I,J),J = 1,13)
19.000      PRINT 9,(A(I,J),J=1,13)
20.000      5 CONTINUE
21.000      CALL MATMD(A,B,74,13,6,1)
22.000      PRINT 6
23.000      11X,'K5',11X,'K6'/)
24.000      DO 7 I = 1,74
25.000      PRINT 8,(I,(A(I,J),J = 1,6))
26.000      PUNCH 11,(A(I,J),J = 1,6)
27.000      7 CONTINUE
28.000      3 FORMAT (13G.0)
29.000      6 FORMAT (1H1,4X,'REACTION',13X,'K1',11X,'K2',11X,'K3',11X,'K4',
30.000      8 FORMAT (5X,14,8X,6(F13.6))
31.000      9 FORMAT(13F10.0)
32.000      10 FORMAT ( 6X,'INDEPENDENT REACTION MATRIX',/)
33.000      11 FORMAT (6F10.3)
34.000      12 FORMAT (///,3X,'TEST = ',14,6X,'IF TEST = 0 , THE SOLUTIONS ARE VAL
35.000      11D')
36.000      14 FORMAT (1H1,5X,'TOTAL REACTION MATRIX',/)
37.000      END

```

Appendix VII Computer program RECALC .

This program calculates the gas fugacity constants for dependent reactions from the gas fugacity constants of the independent reactions and the k constants.

```

1.000 C-----PROGRAM TO CALCULATE CONSTANTS OF REACTIONS FROM EXPERIMENTAL DATA
2.000 C      SCALED FROM FIRST PART OF SKIPPENS XCD PROGRAM
3.000 C      P MOORE OCTOBER 1975
4.000      DIMENSION EXDATA(3,20),RECALC(3,100),RECOEF(20,100),RENAME(14,
5.000      100),CDPOL(100),WAMOL(100)
6.000      99 FORMAT (2G.0)
7.000      100 FORMAT (8F10.3)
8.000      101 FORMAT(3G.0)
9.000      102 FORMAT(1X,10A4,2F5.1,(10F8.3))
10.000     103 FORMAT (10A4)
11.000     READ 99,NUMREA,NUMEXP
12.000     DO 109 I = 1,NUMEXP
13.000       READ 101,(EXDATA(K,I),K = 1,3)
14.000       PRINT 100,(EXDATA(K,I),K = 1,3)
15.000     109 CONTINUE
16.000     PRINT 110,NUMREA
17.000     110 FORMAT (1H1,14,' SETS OF CALCULATION COEFFICIENTS FOR A, B, AND
18.000     1C'/' REACTION DEFINITION                                CDPOL WAMOL CALCULA
19.000     2TION-COEFFICIENTS'/' )
20.000     DO 112 I = 1,NUMREA
21.000       READ 100,(RECOEF(K,I),K = 1,NUMEXP)
22.000     112 CONTINUE
23.000     DO 113 I = 1,NUMREA
24.000       READ 103,(RENAME(K,I),K = 1,10)
25.000     113 CONTINUE
26.000     DO 114 I = 1,NUMREA
27.000       READ 99,CDPOL(I),WAMOL(I)
28.000       PRINT 102,(RENAME(L,I),L = 1,10),CDPOL(I),WAMOL(I),(RECOEF(L,I)
29.000       1 ,L=1,NUMEXP)
30.000       DO 114 J = 1,3
31.000         RECALC(J,I) = RECOEF(1,I)*EXDATA(J,I)
32.000       DO 114 K = 2,NUMEXP
33.000         RECALC(J,I) = RECALC(J,I) + RECOEF(K,I)*EXDATA(J,K)
34.000     114 CONTINUE
35.000     115 PRINT 116,NUMREA
36.000     116 FORMAT (1H1,13,' CALCULATED EQUILIBRIUM DATA FOR AN EQUATION OF
37.000     1THE TYPE LOG K = A/T + B + C(P/TOTAL-2000)/T'/'/' REACT NO',16X,'
38.000     2REACTION',22X,'A',9X,'B',10X,'C'/'/' )
39.000     DO 120 I = 1,NUMREA
40.000       PRINT 119, I,(RENAME(K,I),K=1,10),(RECALC(K,I),K=1,3)
41.000     119 FORMAT (15,5X,10A4,F10.0,F10.3,F10.4)
42.000     120 CONTINUE
43.000     PUNCH 117,((RENAME(K,I),K=1,10),(RECALC(K,I),K=1,3),CDPOL(I),WAMOL
44.000     1 (I),I=1,NUMREA)
45.000     117 FORMAT (10A4,F8.0,F8.3,F8.4,2F5.1)
46.000     CALL EXIT
47.000     END

```

Appendix VIII Computer program ACTIVITY.

This program calculates the logarithm of the fugacities of CO_2 and H_2O of a reaction at three temperatures and three pressures.

```

1.000 C  PROGRAM TO COMPUTE ACTIVITIES OF CD AND WA AT VARIOUS T AND P
2.000 C  R MOORE FEB 1975
3.000 C  DIMENSION REACTION(11,75)
4.000 C  READ 95,NET
5.000 C  95 FORMAT (14)
6.000 C  DO 1000 L = 1,NET
7.000 C  READ 100,(REACTION(I,L),I = 1,10),A,B,C,CD,WA
8.000 C  100 FORMAT (10A4,3F8.0,2F5.0)
9.000 C  PRINT 105,(REACTION(I,L),I = 1,10)
10.000 C  105 FORMAT (1H1,10A4)
11.000 C  P = -2000.
12.000 C  DO 500 J = 1,3
13.000 C  P = P + 4000.
14.000 C  T = 473.15
15.000 C  DO 400 K = 1,4
16.000 C  T = T + 200.
17.000 C  RT = 1./T
18.000 C  RLK = A/T + B + C*(P-2000.)/T
19.000 C  IF (ABS(CD).LT..0001) GO TO 200
20.000 C  IF (ABS(WA).LT..0001) GO TO 210
21.000 C  GO TO 220
22.000 C  200 WAA = RLK/WA
23.000 C  CDD = 0.0
24.000 C  GO TO 410
25.000 C  210 CDD = RLK/CD
26.000 C  WAA = 0.0
27.000 C  GO TO 410
28.000 C  220 CDD = -1.
29.000 C  DO 350 I1 = 1,5
30.000 C  CDD = CDD + 1.
31.000 C  WAA = (RLK-CDD*CDD)/WA
32.000 C  TC = T - 273.15
33.000 C  IF (I1.GT.1) GO TO 250
34.000 C  IF (K.GT.1) GO TO 250
35.000 C  PRINT 240,P
36.000 C  240 FORMAT (//,4X,'PRESSURE =',F7.0,' BARS'/)
37.000 C  PRINT 110
38.000 C  110 FORMAT (14X,'TEMPERATURE C',2X,'LOGCD',4X,'LOGWA',2X,'1/T K',10X,
39.000 C  1 'LOG K'/)
40.000 C  250 PRINT 360,TC,CDD,WAA,RT,RLK
41.000 C  360 FORMAT (12X,F10.0,6X,F6.2,3X,F6.2,4X,F10.8,4X,F10.2)
42.000 C  350 CONTINUE
43.000 C  GO TO 400
44.000 C  410 TC = T - 273.15
45.000 C  IF (K.GT.1) GO TO 420
46.000 C  PRINT 240,P
47.000 C  PRINT 110
48.000 C  420 PRINT 360,TC,CDD,WAA,RT,RLK
49.000 C  400 CONTINUE
50.000 C  500 CONTINUE
51.000 C  1000 CONTINUE
52.000 C  END

```

JOCKO

O RIVER

1B-55-73
2B-55-73
1B-55-73

1d

25
B-55-73

38

27

GEOLOGY OF THE C

== Diabase dyke

Metagabbro

3 Granite gneiss

2 Plagioclase-biotite

Amphibolite

1e Psammitic gneiss

1d Calcilicate gneiss

1c Pelitic gneiss

1b Pyrrhotite gneiss

x Outcrop

7 Semi-continuous outcrop

23 Strike and dip of mineral lineation

23 Mineral lineation

Geological contact

Map 1

GEOLOGY OF THE CROCAN LAKE AREA

- Diabase dyke
- Metagabbro
- Granite gneiss
- Plagioclase-biotite gneiss
- Amphibolite
- Psammitic gneiss
- Calcsilicate gneiss
- Pelitic gneiss
- Pyrrhotite gneiss
- Outcrop
- Semi-continuous outcrop
- Strike and dip of most obvious planar fabric
- Mineral lineation or hinge line
- Geological contact

- JOCKO GNEISS
- ANTOINE GNEISS
- BUTLER GNEISS

B-518-73
B-520-73x

150

70

B-518-73
B-527-73x

31

31A

2

1e

68

B-551-73A

64
40
20

B-658-73
B-657-73

1d

65

1e
1f

B-654-73

1e

86

NO
OUTCROP

55

60

63

NO
OUTCROP

NO
OUTCROP

GEOLOGY

- Diabas
- Granit
- Plagioc
- Amphib
- Psamm
- Calcsil
- Pelitic
- Pyrrho
- Outcro
- Semi-c
- Strike
- Minero
- Geolog

1d

1e

Map 2

OF THE TIMBER LAKE AREA

e, dyke
abbro
e gneiss
ase-biotite gneiss
olite
nitic gneiss
cate gneiss
gneiss
tite gneiss
p

JOCKO GNEISS
ANTOINE GNEISS
BUTLER GNEISS

continuous outcrop
and dip of most obvious planar fabric
all lineation or hinge line
ical contact

Kilometers

$\frac{1}{2}$

1

$1\frac{1}{2}$

$\frac{1}{2}$

1

B-227-72

3

1e,1d

XB-228-72

XB-71-8

XB-230-72

XB-231-72

XB-71-9

XB-232-72

B-233-72

B-234-74

XB-236-72

B-237-72

B-71-13

B-239-72

B-71-14

B-7

FRANCIS

SDT H

TLER TP

1d,1c

B-699-73

2

5-73

B-685-7

1e

NCIS

CREEK

ANTOINE

222-72

2

2

B-248-72X

1e,1d

B-221-72X

B-307-73 X

XB-304-71

B-221-73

B-213-72X

TWIST LAKE

ANTOINE

CREEK

1e

ORIGIA
HILLS

1e

Map 3

GEOLOGY OF THE CAHILL LAKE AREA

- Diabase dyke
 - Monzonitic intrusive
 - Granitic gneiss
 - Amphibolite
 - Psammitic gneiss
 - Calcsilicate gneiss
 - Geological contact
 - Semi-continuous outcrop
 - Strike and dip of most obvious planar fabric
 - Kyanite in amphibolite
 - Conglomerate
- } ANTOINE GNEISS
 } BUTLER GNEISS

55

OF/DE

B-500-73x

501 xB-491

B-508-73

xB-505-73

1e

1e

1e

B-373-73

B-370-73

B-362-73

B-368-73

xB-380-73

35

Antoine

x B-484-73

1e

3

47

60

18

x B-603-73

44

PERRON LAKE

1e

18

OLMSTEAD LAKE

1e

x B-392-73

B-375-73

x B-397-73

CAHILL LAKE

Antoine Creek

x B-484-73

1e

GAUVEREAU LAKE

PERRON LAKE

1e

B-375-73

x B-397-73

1e
B-294-72
B-295-72
B-296-72
B-297-72

1e

LAKE
TALON

B-373-73
-80

B-379-73

B-382-73

B-388-73

B-380-73

1f

46

1f

B-442-73

1e

B-445-73

1e

35

45

LAKE

1e

B-392-73

B-375-73

x B-397-73

CAHILL LAKE

TEESDALE LAKE

B-417-73

x B-411-73

1e

B-407-73

45

1e

B-375-73

1f

B-397-73

52

ESDALE
LAKE

B-417-73

B-411-73

35

1e

B-405-73

B-407-73

1e

GEOLOGY OF THE MINER'S LAKE AREA

- Plagioclase-biotite gneiss } ANTOINE GNEISS
- Psammitic gneiss }
- Calcisilicate gneiss } BUTLER GNEISS
- Pelitic gneiss }
- Pyrrhotite gneiss }
- Marble }
- Outcrop
- Semi-continuous outcrop
- Strike and dip of most obvious planar fabric
- Mineral lineation or hinge line
- Geological contacts
- Trench

Kilometers

1/2

Miles

McDougal Lake

WYSE TP
CLARKSON TP

1b

1

1

1b

winers

1e

CLARKSON TP
JOCKO TP

6-7-72
6-7-72

B-2-72

Temiskaming

OTTAWA

QUEBEC
ONTARIO

B-53-78
55

B-52-78

Map 5

COMPILATION MAP OF THE MATTAWA-NORTH BAY-TEMISCAMING

Diabase dyke

Quartz monzonite

Metaperidotite

Metagabbro

Monzonitic intrusive

Granitic gneiss

Plagioclase-biotite gneiss

Amphibolite

Psammitic gneiss

Calcsilicate gneiss

} JOCKO

} ANTO

} RITI

OF THE
MISCAMING AREA

} JOCKO GNEISS
} ANTOINE GNEISS

} BUTLER GNEISS

BUT

Pelitic gneiss

Pyrrhotite gneiss

Marble

Geology - R.L. Moore

Geology - interpreted from S.B. Lu

Kilometers

0 1 2 3 4

0

1

2

Miles

oxeys Camp

1e

d

BUTLER GNEISS

om S.B. Lumbers 1971

FRENCH TP
PHELPS TP

NO OUTCROP

B-71-72x

1e

HIGHWAY 63

Bottom
Creek

3

2

1e

B-71-129

1d

1f

B-71-66

Snake
Creek

La Cave

ANTOINE
PROVINCIAL PARK

B 71 12
1d 1f
B 71 66
B 71 66

3

1e

2

RIVER

MATTAWA

5a

Lake
Robichaud

TURTLE LAKE

5b

2

3

BOONFIELD T.P.
EAST FERRIS T.P.

HIGHWAY 17

ANTOINE
PROVINCIAL PARK

Creek

3

Mattawa

Earl
lake

FAU
11B

78°45'

JOCKO

RIVER

Map

ASSEMBLAGE CROCAN LA

Minerals present

Bi-Cc-Qz-Hb-Pf-Ep

Bi-Cc-Qz-Hb-Pf-Ep-Kf

Bi-Qz-Hb-Pf-Ep-Kf

Bi-Cc-Qz-Kf-Di-Pf-Ep

Ph-Qz-Di-Hb-Ep-Pf

kilom

0

0

1/4

Mi

Map 6

ASSEMBLAGE MAP OF THE CROCAN LAKE AREA

Minerals present	Symbol	Assemblage Number
Bi-Cc-Qz-Hb-Pf-Ep	○	1
Bi-Cc-Qz-Hb-Pf-Ep-Kf	◐	2
Bi-Qz-Hb-Pf-Ep-Kf	●	3
Bi-Cc-Qz-Kf-Di-Pf-Ep	◑	5
Ph-Qz-Di-Hb-Ep-Pf	△	11

6081

807

TREMBLAY
LAKE

CROCAN LAKE

TIMBER
LAKE

Temiskaming

OTTAWA

QUEBEC
ONTARIO

Eldee

POITRAS TP
EDDY TP

Map 7

ASSEMBLAGE MAP OF THE MATTAWA-NORTH BAY-TEMISCAMING

Minerals present

Symbol Ass
 No

Bi-Cc-Qz-Hb-Pf-Ep

○

Bi-Cc-Qz-Hb-Pf-Ep-Kf

●

Bi-Qz-Hb-Pf-Ep-Kf

●

Bi-Qz-Kf-Di-Hb-Ep-Pf

▲

Bi-Cc-Qz-Kf-Di-Pf-Ep

●

Mv-Cc-Qz-Ep-Pf-Bi

◇

Mv-Cc-Qz-Kf-Ep-Pf-Bi

◇

Bi-Cc-Qz-Di-Hb-Ep-Pf

■

OF THE
CAGING AREA

of Assemblage
Number

1

2

3

4

5

6

7

8

9

CLARKSON TP
JOCKO TP

Jocko

HIGHWAY 63

Little

JOCKO TP
FRENCH TP

Koko
Lake

Jocko

Butler
Lake

Francis

POITRAS TP
EDDY TP

RIVER

ver
River

604

Jocko
River

EDDY TP
BUTLER TP

Tremblay
Lake

Sparks
Lake

Crocan
Lake

Coxey

HIGHWAY 533

MV-Cc-Qz-Kf-Ep-Pf-Bi

Bi-Cc-Qz-Di-Hb-Ep-Pf

Bi-Cc-Qz-Di-Ep-Pf

Bi-Cc-Qz-Kf-Di-Hb-Ep-Pf

Kilometers

0

1

2

3

4

5

Miles

0

1

2

3

eys Camp

7

8

9

10

5

3

806

FRENCH TP
PHELPS TP

HIGHWAY 63

Balsom

North

Creek

Snake
Creek

Bangs
Bay

QUEBEC
ONTARIO
RIVER

ANTOINE
PROVINCIAL PARK

La Cave

HIGHWAY 533

Antoine

Kearney Lake

OLRIG TP
MATTAWAN TP

AWA

RIVER

PAPINEAU TP
CALVIN TP

HIGHWAY 17

Smith
Lake

ANTOINE
PROVINCIAL PARK

Creek

Mattawa

Earl
Lake

CHIEAU TP

78°45'

47°00'

46°45'

Lake

TMG 1 2-73

FRONT

Temiscaming

GRENVILLE

GF-3-73

GF-7-73

GF-8-73

9

10

GF-11-73

12

13

GF-14-73

B-205
208
209
210
211
212

ASSEMBLAGE MAP GRENVILLE

Minerals present

Bi - Cc - Qz - Hb - Pl - Ep

Bi - Cc - Qz - Hb - Pl - Ep - Kf

Bi - Qz - Hb - Pl - Ep - Kf

Bi - Qz - Kf - Di - Hb - Ep - Pl

Bi - Cc - Qz - Kf - Di - Pl - Ep

Mv - Cc - Qz - Ep - Pl - Bi

Mv - Cc - Qz - Kf - Ep - Pl - Bi

Bi - Cc - Qz - Di - Hb - Ep - Pl

Bi - Cc - Qz - Di - Ep - Pl

Bi - Cc - Qz - Pl - Di - Hb - Ep - Pl

Ph - Qz - Di - Hb - Ep - Pl

0

0

ONTARIO
QUEBEC

Temiscaming

TMG-24-73

TMG-17-73

19

TMG-21-73

22

TMG-8,9,10-73

Wabigoon Point

TMG-13,14,15-73

TMG-29

Map 8

ASSEMBLAGE MAP OF THE NORTHEAST GRENVILLE GNEISS TERRAIN

Minerals present	Symbol	Assemblage Number
Bi-Cc-Qz-Hb-Pt-Ep	○	1
Bi-Cc-Qz-Hb-Pt-Ep-Kf	●	2
Bi-Qz-Hb-Pt-Ep-Kf	●	3
Bi-Qz-Kf-Di-Hb-Ep-Pf	▲	4
Bi-Cc-Qz-Kf-Di-Pt-Ep	●	5
Mv-Cc-Qz-Ep-Pt-Bi	◇	6
Mv-Cc-Qz-Kf-Ep-Pt-Bi	◆	7
Bi-Cc-Qz-Di-Hb-Ep-Pf	■	8
Bi-Cc-Qz-Di-Ep-Pf	○	9
Bi-Cc-Qz-Kf-Di-Hb-Ep-Pf	*	10
Ph-Qz-Di-Hb-Ep-Pf	△	11

TMG-17-7
19

TMG-21-7
22

va

680 73

River

B-681-73
682
683

Provincial Park

78°30'

78°15'

6026

END

140377

FIN