GARNET-CORDIERITE-ANTHOPHYLLITE ROCKS
AT RAT LAKE, MANITOBA

A THESIS PRESENTED TO
THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF
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MASTER OF SCIENCE

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ABSTRACT

Anthophyllite - garnet - cordierite rocks occur in the PreCambrian of the Churchill province at Rat Lake, Manitoba. Texturally the rocks can be classified as granoblastites, porphyroblastites and schists. They occur in an area of deformed meta-sedimentary rocks that have been intruded by granodiorite, tonalite, granite and pegmatite. Three outcrops of the anthophyllite - garnet - cordierite rocks, covering and area of 200' x 90' were mapped on a scale of 1" ≑ 10' and ninety-seven samples were collected. Chemical analyses were obtained for 10 whole rock samples, also for garnets separated from seven samples, and one sample of cordierite. Compositions of other cordierite and anthophyllite specimens were determined by measuring optical properties.

Mineral relationships can be interpreted to have originated in two stages of metamorphism. An early high pressure, high temperature period of granulite metamorphism is evidenced by the relict mineral assemblage orthopyroxene - sillimanite - garnet - cordierite (?). A later retrograde garnet - cordierite grade of metamorphism of the uppermost amphibolite facies is indicated by the assemblage garnet - cordierite - anthophyllite - hercynite, (the garnet of this assemblage being a relict of the granulite grade metamorphism) plus textural evidence of reactions which are interpreted to be:

Garnet + sillimanite ⟶ cordierite + hercynite (1)
Orthopyroxene + quartz + water ⟶ anthophyllite (2)
Anthophyllite + hercynite ⟶ cordierite (3)

The presence of relict bedding, and unusual rock compositions support a theory of origin of these rocks as a weathering deposit from basic rocks.

CHAPTER I

INTRODUCTION

Rat Lake is located approximately 80 miles N.W. of Thompson, Manitoba.

The location of anthophyllite - garnet - cordierite bearing rocks is shown in the inset of Plate No. 1 (pocket at back). Mapping of the outcrops and collection of samples was conducted during the summer 1969, while the author was employed by the Manitoba Mines Branch. The area was revisited in the summer of 1970.

In the Rat Lake area, pelitic rock of the Wasekwan series are overlain by arkosic rocks of the Sickle Series.

The rocks at Rat Lake are Archean in age and are complexly deformed. The oldest rocks in the area are a layered sequence of pelitic gneisses (meta-greywackes) that have been interpreted to belong to the Wasekwan series. The mineralogy of these rocks is quartz, plagioclase, biotite, garnet, cordierite, sillimanite ± graphite. Stratigraphically above the pelitic gneisses is a thin band of amphibolite; it is not continuously exposed, but correlation with magnetic maps indicates that it is persistent, and Campbell (1971) puts this unit in the lower part of the Sickle series. The Sickle rocks are a sequence of quartzo - feldspathic gneisses, generally red to reddish brown and dark brownish grey, their mineralogy is simple, quartz, alkali feldspar, biotite, ± sillimanite and garnet, and their regional metamorphic grade is upper amphibolite facies (Schledewitz, 1969, and Elphick, 1969).

The anthophyllite - garnet - cordierite rocks are located at the stratigraphic level of the amphibolite. Texturally these rocks are granoblastic, prophyroblastic and schists. In contrast to the surrounding rocks, the anthophyllite - garnet - cordierite rocks do not show complex deformation on micro or meso scale.

CHAPTER II

STRUCTURE

The deformation in the Rat Lake Area is very complex, and a complete account of the structure is given by Schledewitz (1971). In brief, evidence of an early deformation has been largely obscured by later complex deformational events. The earliest recognizable event consists of large scale, gentle, open folding, with an E-W axial plane. A second phase imposed on the first, is represented by tight isoclinal folding with a NW-SE axial plane. The basin and dome outcrop pattern of much of the area is the result of the interference effect of these folds. The third and most penetrative has an axial plane sub-parallel to the E-W direction of the first deformational event, and has produced a general E-W foliation in the Rat Lake Area. A late strong N-S shear direction is a prominent feature in the area.

The anthophyllite - garnet - cordierite rocks occur at the same stratigraphic horizon as the amphibolite that lies between the Wasekwan pelitic gneisses and the Sickle quartzo-feldspathic gneisses.

The outcrop (Plate 1) shows bedding, irregular folds and repetition of beds, which indicate a folded structure with an axial plane striking NW-SE; the plunge of this axis cannot be determined. An axial planar schistosity is well developed in the schists, units # 2, 3, and 5.

The anthophyllite - garnet - cordierite rocks do not display the penetrative foliation, associated with the third deformation, that is seen in the adjacent pelitic rocks. A ductility contrast may have existed between the two rock types, the anthophyllite rich rocks being more competent, and thus the later regional foliation is not developed.

CHAPTER III

MICROFABRICS

In contrast to the complex tectonic fabrics in the surrounding rocks, nematoblastic, porphyroblastic and granoblastic textures predominate in the anthophyllite - garnet - cordierite rocks. The microfabrics described below relate to the mineral assemblages within map units called schists, granoblastites and porphyroblastites (units # 2, 3, 5 to 14).

The anthophyllite - garnet - cordierite schists typically display a nematoblastic texture, with biotite and anthophyllite orientated with their greatest dimension (a-axis of biotite and c-axis of anthophyllite) parallel or sub-parallel to the schistosity (Fig. 1).

Most garnets are porphyroblastic and idioblastic (Fig. 2). Some xenoblastic crystals have an inclusion free core and an outer rim that is full of inclusions of anthophyllite, biotite and cordierite. These xenoblastic garnets generally have a reaction rim of cordierite ± hercynite surrounding them (Fig. 3). The texture in the reaction rim consists of granular cordierite, with some wormy intergrowths of quartz and/or hercynite and/or anthophyllite (Fig. 3-1). The development of this texture is interpreted to be due to a second period of recrystallization, (retrogression from granulite facies).

Cordierite knots are porphyroblastic with an internal granoblastic texture (Fig. 4). Hercynite in these knots is granoblastic (Fig. 4 and 5), and if sillimanite is present displays a wormy intergrowth with cordierite (Fig. 6). This texture is thought to represent the reaction(1), garnet + sillimanite $\longrightarrow$ cordierite + hercynite. Figure 7 shows knots of cordierite associated with garnets of various sizes; garnet has reacted

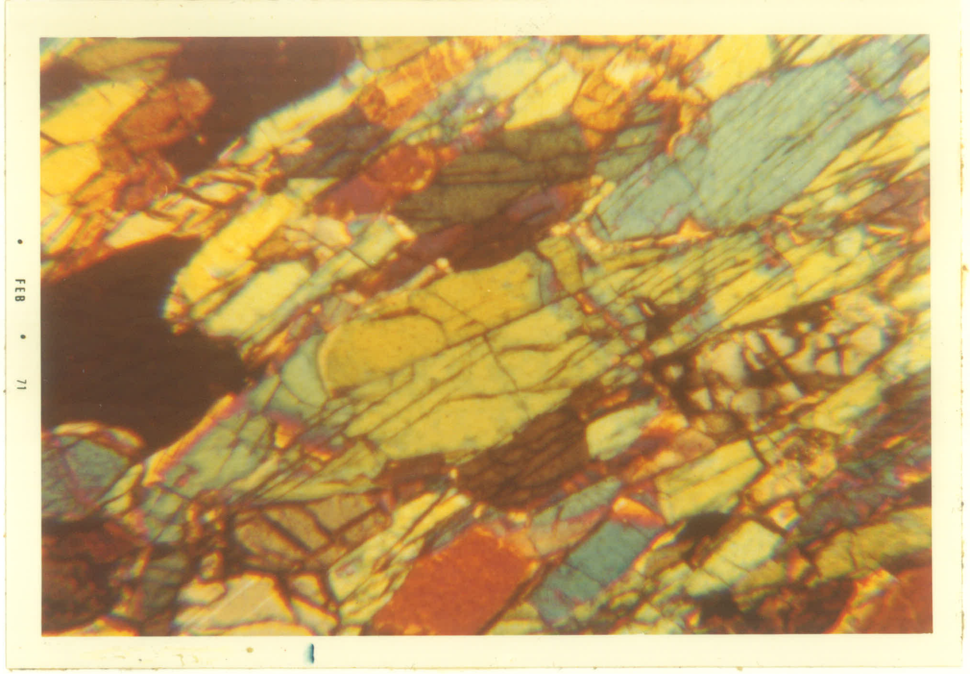

Fig. 1; Nematoblastic texture in the anthophyllite - garnet - cordierite schists. Sample DF-2. (X-Nicols; X 4).

Fig. 2; Garnet porphyroblasts displaying idioblastic outlines.

Fig. 3; Reaction rim of cordierite and hercynite surrounding garnet porphyroblast. Sample EJ-8.

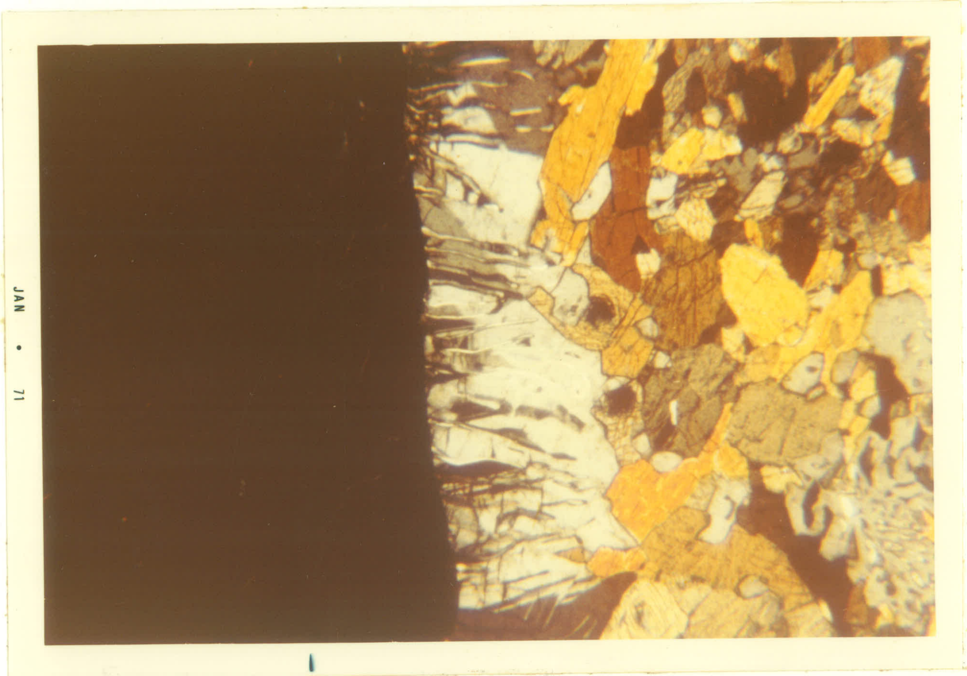

Fig. 3-1; Thin section of cordierite reaction rim around garnet porphyroblast. Sample CI-6. (X-Nicols; X 2.5).

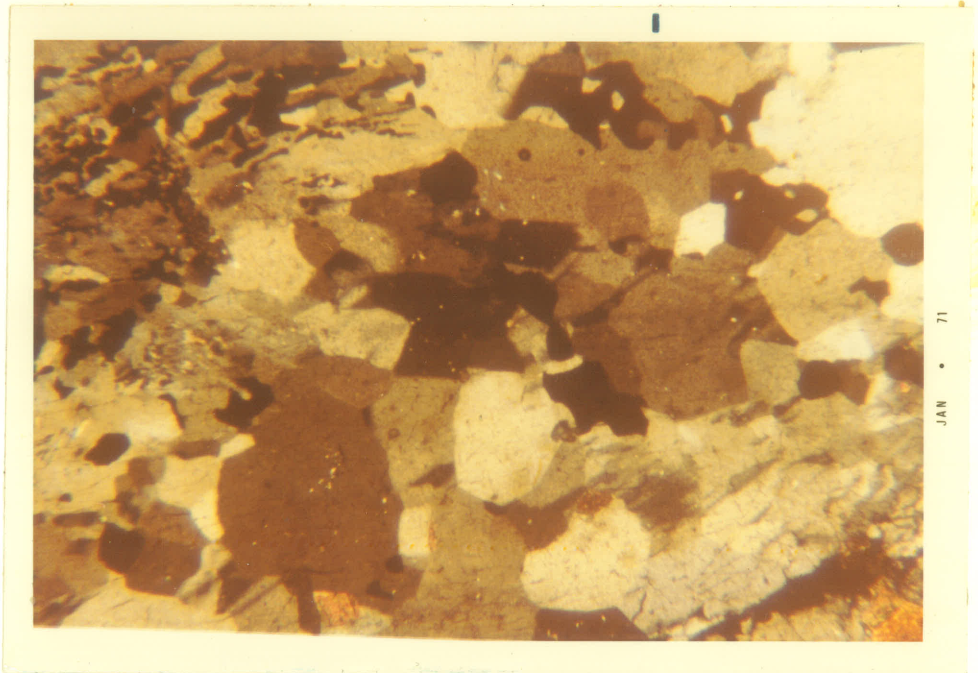

Fig. 4; Thin section showing granular texture in cordierite knots. Sample EI-6. (X-Nicols; X 25).

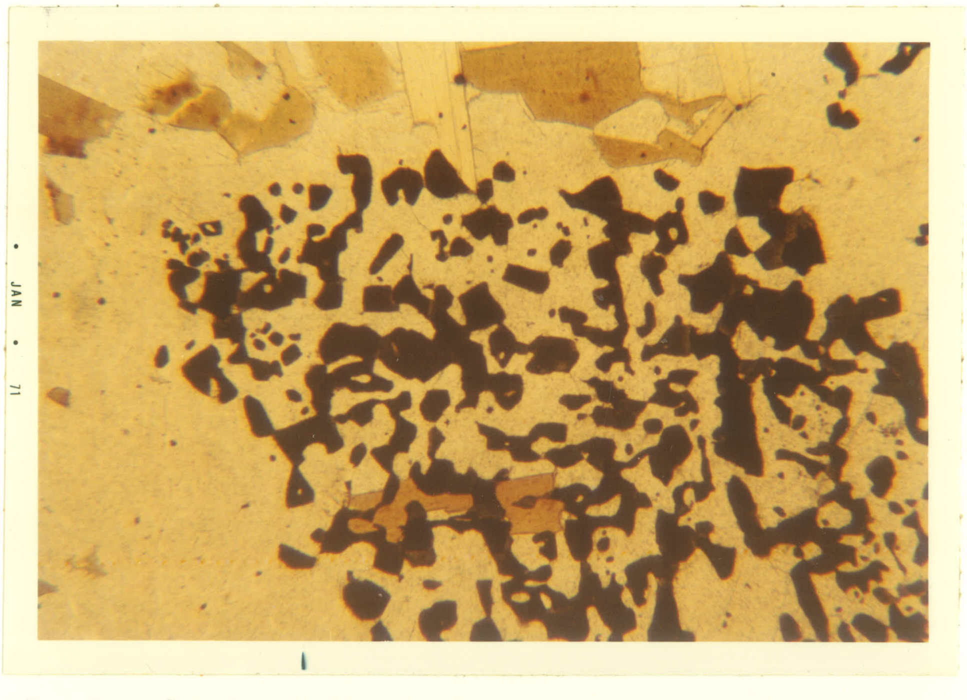

Fig. 5; Granular hercynite in absence of sillimanite. Sample FI-11 (plane polarized light; X 25).

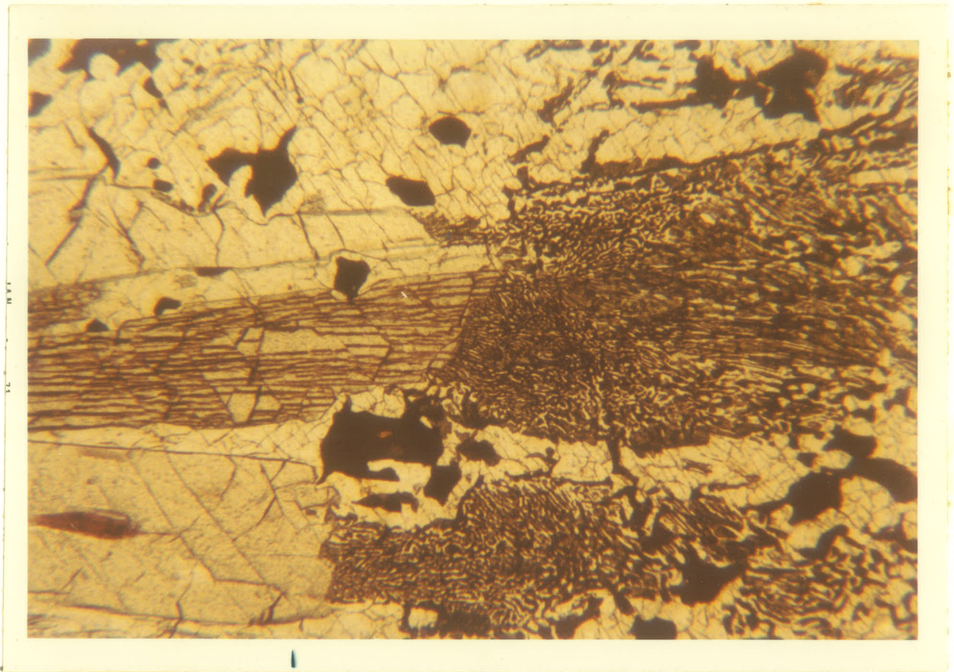

Fig. 6; Wormy growth of hercynite in presence of sillimanite. Sample EI-6. (plane polarized light; X 25).

Fig. 7; Cordierite knots pseudomorphous after garnet (unit 8).

where sillimanite was included or adjacent to itl

Cordierite also occurs interstitially between anthophyllite and hercynite. Both minerals show corrosion edges (Fig. 8). Reaction (3) anthophyllite + hercynite $\longrightarrow$ cordierite is interpreted from this relationship.

Cordierite in the quartzitic rocks (unit #1, Plate 1) contains inclusions of fibrolite. Numerous quartz inclusions were observed in one large poikiloblastic cordierite.

Polysynthetically twinned cordierite is abundant.

Anthophyllite is nematoblastic, except in units 11 and 12 where, in the presence of relict pyroxene, it has a feathery radial crystal growth. The pyroxene forms the nucleus from which the radial anthophyllite grows (Fig. 9). This is textural evidence for reaction (2), orthopyroxene + quartz + water $\longrightarrow$ anthophyllite.

Magnetite is present as equidimensional grains disseminated throughout the rocks. One notable exception is Unit #7, a magnetite granoblastite. The rock has granoblastic texture with fine unidentified interstitial material filling the nearly sub-microscopic spaces between magnetite grains (Fig. 10).

No textural evidence was seen for proposing two periods of deformation, (i.e. cross-cutting relations in the microfabrics).

The presence of clear cores and inclusion riddled outer rims of garnets would be taken by some workers as evidence of two phases of garnet growth. Without knowing if there is a difference in the composition of the cores and rims, plus the absence of a secondary phase associated with the garnet, the author does not wish to propose two periods of garnet growth in these rocks.

Garnet porphyroblasts are highly fractured but not rolled. The absence of pull-apart structure of the schistose fabric by garnet porphyroblasts, the idiomorphism of the garnet and absence of inclusions (uncommon) indicate complete recrystallization of the rocks (Fig. 11).

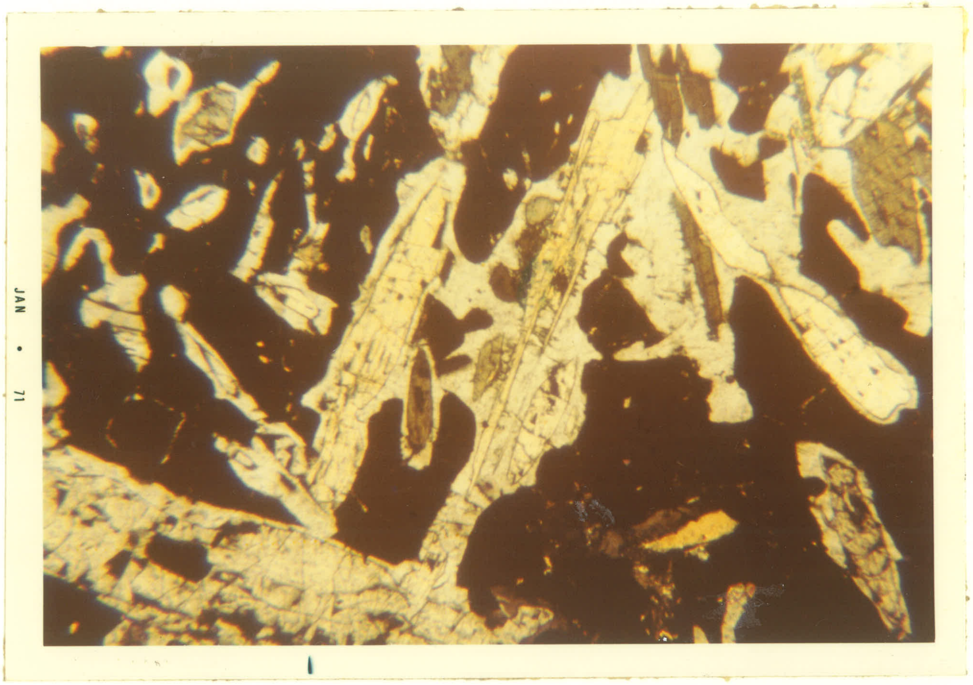

Fig. 8; Relationship between hercynite and anthophyllite showing corrosion edges and interstitial cordierite. Sample FM-1- (X-Nicols; X 25).

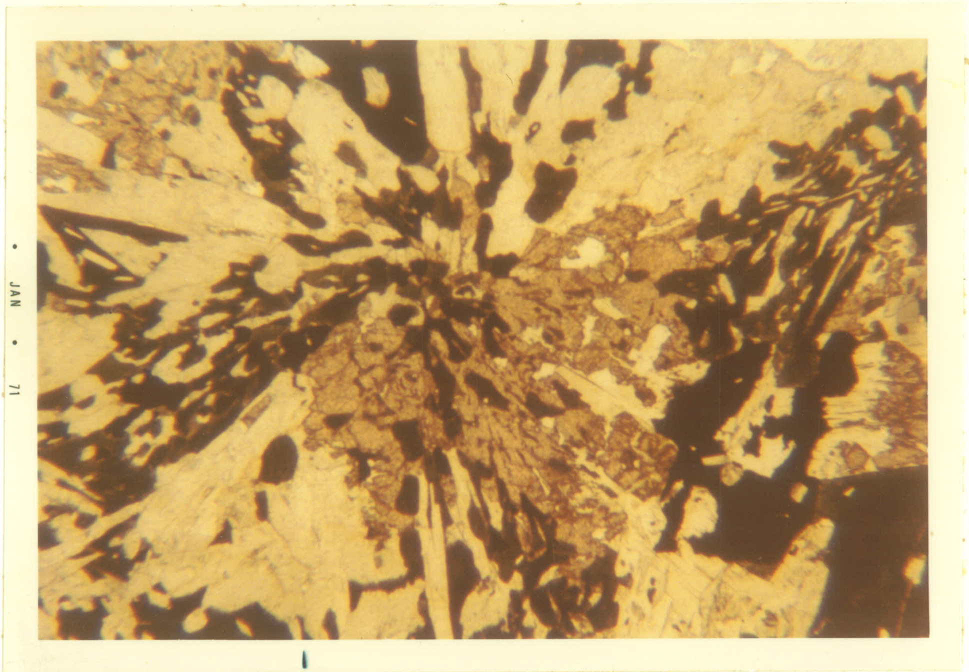

Fig. 9; Radiating amphibole with pyroxene nucleus. Sample BG-3. (plane polarized light; X 25).

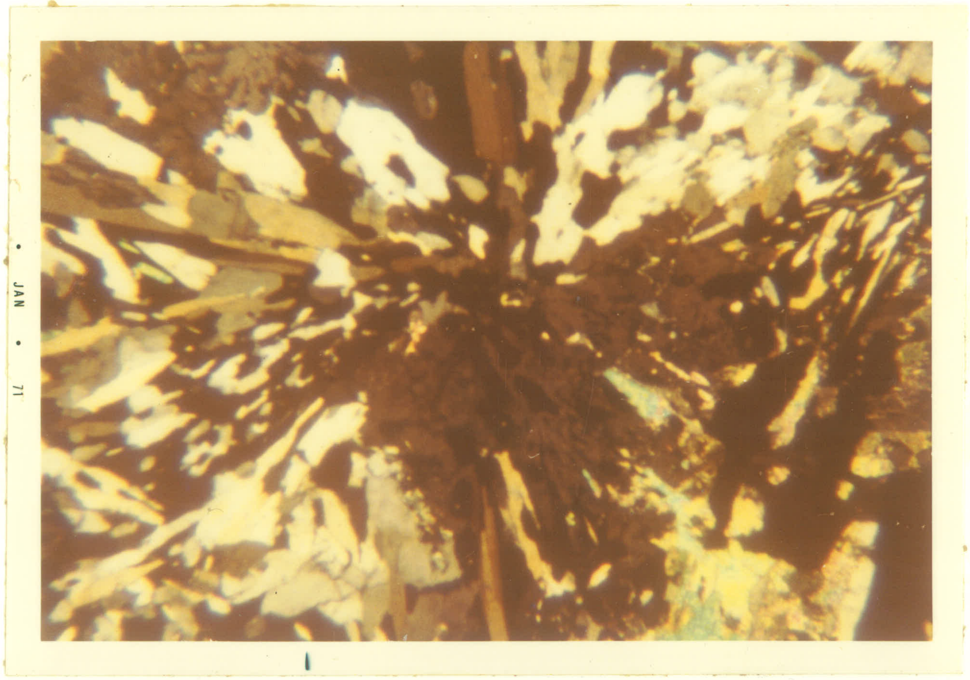

Fig. 9-1; Radiating amphibole with pyroxene nucleus. Sample BG-3 (X-Nicols; X 25).

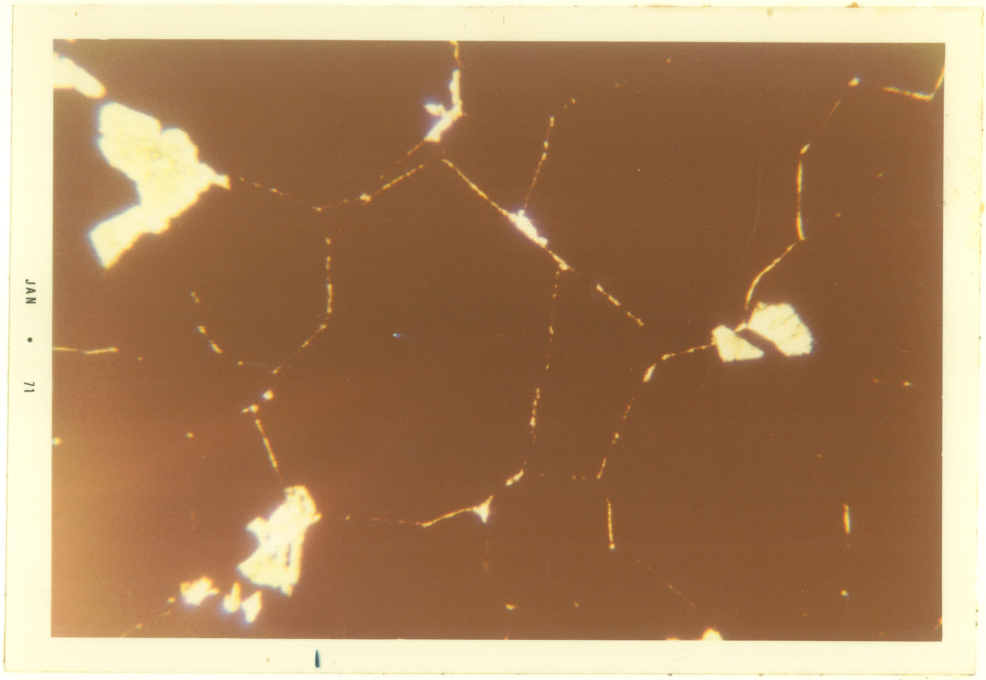

Fig. 10; Magnetite granoblastite. Note fine grained material filling spaces between magnetite crystals. Sample BH-5. (plane polarized light; X 25).

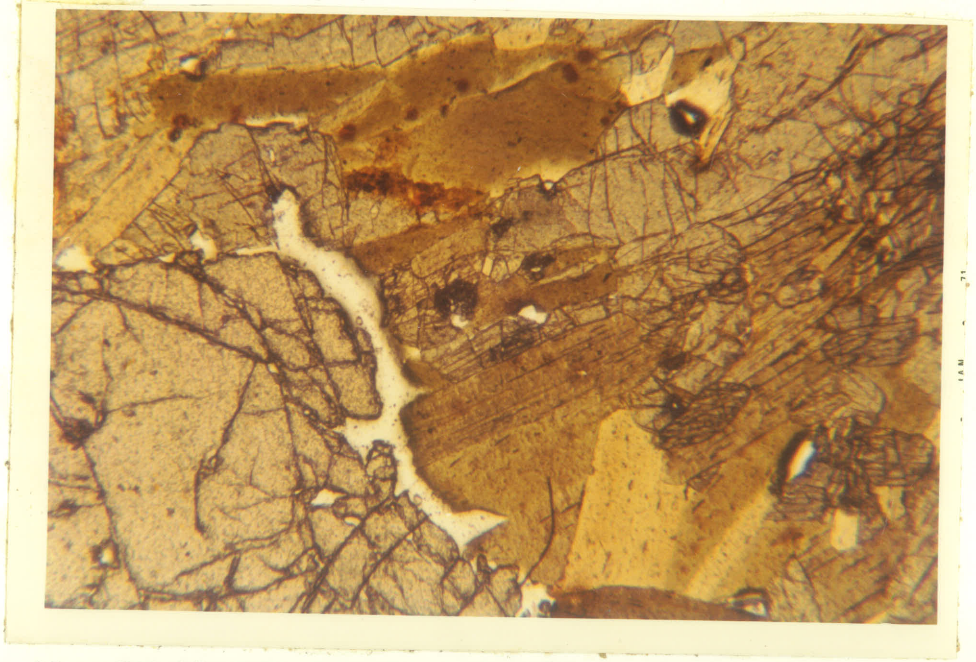

Fig. 11; Idioblastic garnet porphyroblast showing absence of push-apart structure and absence of inclusions. Sample EI-6. (plane polarized light; X 25).

CHAPTER IV

COMPOSITION AND PETROGRAPHY

The chemical composition of ten whole rock samples is given in Table 1, the Niggli norms of these samples are given in Table 2. Table 3 shows mineral modal analyses of the rocks. The locations of the ten rocks analysed are given in Fig. 12, and their composition plotted on Fig. 13.

The rocks (Table 1) are basic in composition, the SiO_2 content being less than 50%. The rocks are rich in MgO, FeO and Al_2O_3, with very little alkali component and negligible CaO. One analysis of vermiculite clay and one of a hypersthene gabbro are given for comparison. The SiO_2, Al_2O_3 and Fe_2O_3 values for the vermiculite clay are similar to the values for the rocks concerned with in this work, the FeO being low and MgO high. The SiO_2, Al_2O_3, FeO and MgO are in good agreement to those for phyersthene gabbro, but the Fe_2O_3 of the gabbro is low and CaO high. The high content of total iron in sample BH-5 (90% magnetite in the mode), and the relict bedding structure in this rock, unit #7, suggest that it is probably a metamorphosed sedimentary iron formation.

Table 1-1 shows analyses of two samples from table 1, plus Sample A, the average composition from 9 samples in table 1 (omitting sample BH-5), that have been recalculated to 100% after the addition of 5 wt.% CaO. Since basic igneous rocks contain an average of 5 wt.% CaO this amount was added to the analysis to determine the approximation of the rocks to a basic igneous rock composition. Sample R-524, B and C are put in for comparison. From the comparison it is seen that the chemistry of the Rat Lake rocks is similar to that of basic igneous rocks from which calcium and Na + K have been leached, although no evidence of such a process was observed.

The chemistry of the rocks is reflected by the mineralogy. Modally, anthophyllite, cordierite and garnet are the most abundant minerals present; anthophyllite $>$ cordierite $>$ garnet (Table 3). Biotite is the next most abundant mineral followed by hercynite, magnetite, pyroxene, sillimanite and zircon.

Anthophyllite:

The composition of five samples of anthophyllite was determined from measurements of the refractive index and $2V_z$ (Fig. 14). (Deer, Howie and Zussman, 1966).

Anthophyllite occurs as short, well formed prismatic crystals, commonly in a parallel orientation (nematoblastic), more rarely in radiating clusters. Its pleochroic formula is:

$\alpha = \beta$ = pale green - grey

γ = colorless to pale green.

Anthophyllite shows reaction textures when in contact with hercynite with the formation of a rim of cordierite between the two minerals. No other disequilibrium textures involving anthophyllite are present, except with hercynite.

Garnet:

Seven garnets were separated with heavy liquids (methylene iodide). Chemical analysis of the garnets is shown in Table 4. The location of the analyzed garnet samples is shown in Fig. 12.

The analysis shows that the garnets are almandine in composition, in terms of mole % end members the garnets are almandine 52% pyrope 38% and spessartite 10%.

TABLE 1

Chemical analysis (whole rock) in wt.% Done by X-Ray Fluorescence. Analyst K. Ramlal

Sample No.	FB-1	EF-3	BG-3	BH-5	G1-1	FM-10	10-2	IP-3	JR-7	HS-2	1	11
SiO_2	47.90	49.40	38.60	3.40	40.25	35.70	41.15	39.45	39.60	32.55	41.70	46.96
Al_2O_3	28.02	15.32	16.86	1.49	19.86	20.15	20.22	21.60	21.58	19.93	23.25	14.13
Fe_2O_3	2.91	4.68	6.59	61.69	4,84	7.40	3.88	3.85	5.48	11.38	6.05	0.76
FeO	10.44	12.48	13.28	27.62	15.80	15.56	14.84	14.68	13.56	15.84	0.75	14.95
MgO	8.30	14.40	20.20	3.40	14.70	16.70	15.00	14.80	15.10	15.70	28.35	15.97
CaO	0.00	0.00	0.00	0.00	0.03	1.10	0.02	0.50	0.10	0.11	-	2.32
Na_2O	0.16	1.00	1.04	0.03	1.06	1.48	1.52	1.40	1.40	1.32	-	0.35
K_2O	0.70	0.70	0.09	0.00	0.90	0.12	0.54	0.61	0.41	0.10	-	1.68
H_2O	0.52	1.52	1.86	0.75	1.14	1.26	1.62	1.62	1.55	1.84	-	1.33
CO_2	0.14	0.29	-	0.03	0.19	-	0.14	0.11	0.16	0.19	-	-
TiO_2	0.14	0.23	0.08	0.07	0.31	0.33	0.28	0.33	0.31	0.34	-	0.62
ZrO_2	0.07	0.08	0.03	0.00	0.12	0.09	0.08	0.09	0.08	0.09	-	-
S	0.00	0.00	0.119	0.01	0.01	0.34	0.01	0.01	0.00	0.04	-	-
MnO	0.10	0.10	0.14	0.07	0.07	0.13	0.08	0.07	0.07	0.08	-	0.93
Total	99.40	99.57	98.88	98.56	99.28	100.36	99.38	99.12	99.40	99.514	100.00	100.00

NOTE: See page 16 for sample description.

FB-1; Cordierite - garnet - biotite schist.

EF-3; Cordierite - garnet - anthophyllite schist.

BG-3; Magnetite - amphibole porphyroblastite.

BH-5; Magnetite granoblastite.

GI-1; Cordierite - garnet - anthophyllite porphyroblastite.

FM-10; Magnetite amphibolite.

IO-2; Garnet - cordierite - anthophyllite schist.

IP-3; Cordierite - garnet - anthophyllite porphyroblastite.

JR-7; Garnet - cordierite - anthophyllite schist.

HS-2; Magnetite - garnet - anthophyllite porphyroblastite.

1; Yelloish brown vermiculite, Corundum Hill, North Carolina (Chatard,1887) recalculated to 100% after removal of 22.47 wt. % H_2O.

11; Hypersthene Gabbro, Gunflint Minn. (From Clarke, F.W. 1924).

TABLE 1-1

Sample No.	EF 3	IO-2	A	R-524	B	C
SiO_2	47.23	39.42	39.77	45.7	35.56	30.24
Al_2O_3	14.65	19.37	19.90	11.45	11.25	16.83
Fe_2O_3	4.48	3.71	5.52	2.64	6.62	3.95
FeO	11.93	14.21	13.72	10.16	6.67	18.72
MgO	13.77	14.37	14.74	19.5	14.68	16.73
CaO	4.80	4.90	5.17	6.92	8.99	1.92
Na_2O	0.95	1.45	1.12	0.62	3.86	0.27
K_2O	0.07	0.51	0.39	NIL	1.70	0.02
H_2O	1.45	1.55	1.40	1.80	1.72	10.45
CO_2	0.27	0.14	0.16	0.41	-	0.08
TiO_2	0.21	0.27	0.24	0.29	8.03	0.58
ZrO_2	0.08	0.08	0.07	-	-	-
S	0.007	0.01	0.06	0.02	-	-
MnO	0.09	0.08	0.08	0.20	-	0.28

EF-3	Recalculated to 100% after addition of 5 wt.% CaO
IO-2	Recalculated to 100% after addition of 5 wt.% CaO
A	Average of 9 analysis from Table 1, recalculated to 100% after addition of 5 wt.% CaO
R-524	Cortlandtite, Beresford Lake Area, Southeastern Manitoba; Ultramafic rocks of the Rice Lake Greenstone Belt; R. F. J. Scoates in Man. Mines Br. pub. 71-1 (in press).
B	Melilite - Basalt; Hohenatoffeln, Hegau, baden, Grubenmann, analyst. Inaug. Dissert, Zurich, 1886, 35. (partial analysis)
C	M. Vuagnat, Variolites et spilites, Archiv. Sci., Vol. 2, fasc. 2, p. 235, 1949. (partial analysis).

TABLE 2

NIGGLI NORMS

SAMPLE No.	FB-1	EF-3	BG-3	BH-5	GI-1	FM-10	IO-2	IP-3	JR-7	HS-2
Saturation Index	23.0	12.5	-6.0	-2.3	-2.4	-9.6	-2.7	-4.2	-1.6	-7.3
Differentiation Index	28.7	22.1	9.9	0.3	15.0	13.9	17.0	16.3	15.0	12.8
Colour Index	41.0	62.3	25.5	94.0	12.8	37.8	12.7	17.2	11.1	34.8
Calcite	-	-	-	-	0.06	-	0.040	0.281	0.200	0.225
Pyrite	-	0.026	0.314	0.035	0.026	0.884	0.026	0.026	0.026	0.107
Ilmanite	0.198	0.326	0.111	0.131	0.183	0.458	0.393	0.464	0.434	0.487
Orthoclase	4.227	0.423	0.536	-	5.415	0.708	3:227	3.651	2.443	0.609
Albite	1.464	9.168	9.392	0.363	9.671	13.255	13.774	12.706	12.648	12.204
Anorthite	-	-	-	-	-	5.453	-	1.808	-	-
Magnetite	3.097	4.988	6.918	86.153	5.133	7.704	4.087	4.062	5.755	12.231
Hematite	-	-	-	0.729	-	-	-	-	-	-
Corundum	30.049	15.158	16.524	2.120	19.010	16.964	18.875	19.838	20.924	19.837
Enstatite	23.558	40.930	-	-	-	-	-	-	-	-
Ferrosilite	14.198	16.036	-	-	-	-	-	-	-	-
Hypersthene	-	-	47.986	3.381	52.799	25.735	51.167	44.444	52.556	32.129
Quartz	23.024	12.565	-	-	-	-	-	-	-	-
Olivene	-	-	18.215	7.034	7.485	28.834	8.248	12.715	4.907	22.033

TABLE 3

Mineral Modes - Analysis by Point Counting

1,000 points per section

SAMPLE No.	FB-1	EF-3	BG-3	BH-5	GI-1	FM-10	IO-2	IP-3	JR-7	HS-2
Biotite	13.5	1.0	2.0		13.0	3.0	7.0	No section for this sample	6.5	1.0
Cordierite	73.0	39.0	.5		14.0	3.5	18.0		26.0	1.0
Garnet	2.5		2.0		7.0				26.0	0.5
Anthophyllite	9.0	60.0	79.0		65.0	62.0	63.0		34.0	72.5
Pyroxene			9.0	5.0		0.5				
Zircon			1.0		minor					
Hercynite			6.5	5.0	minor	31.0	12.0		herc + mt 7.0	25.0
Magnetite				90.0						
Sillimanite	2.0								0.5	

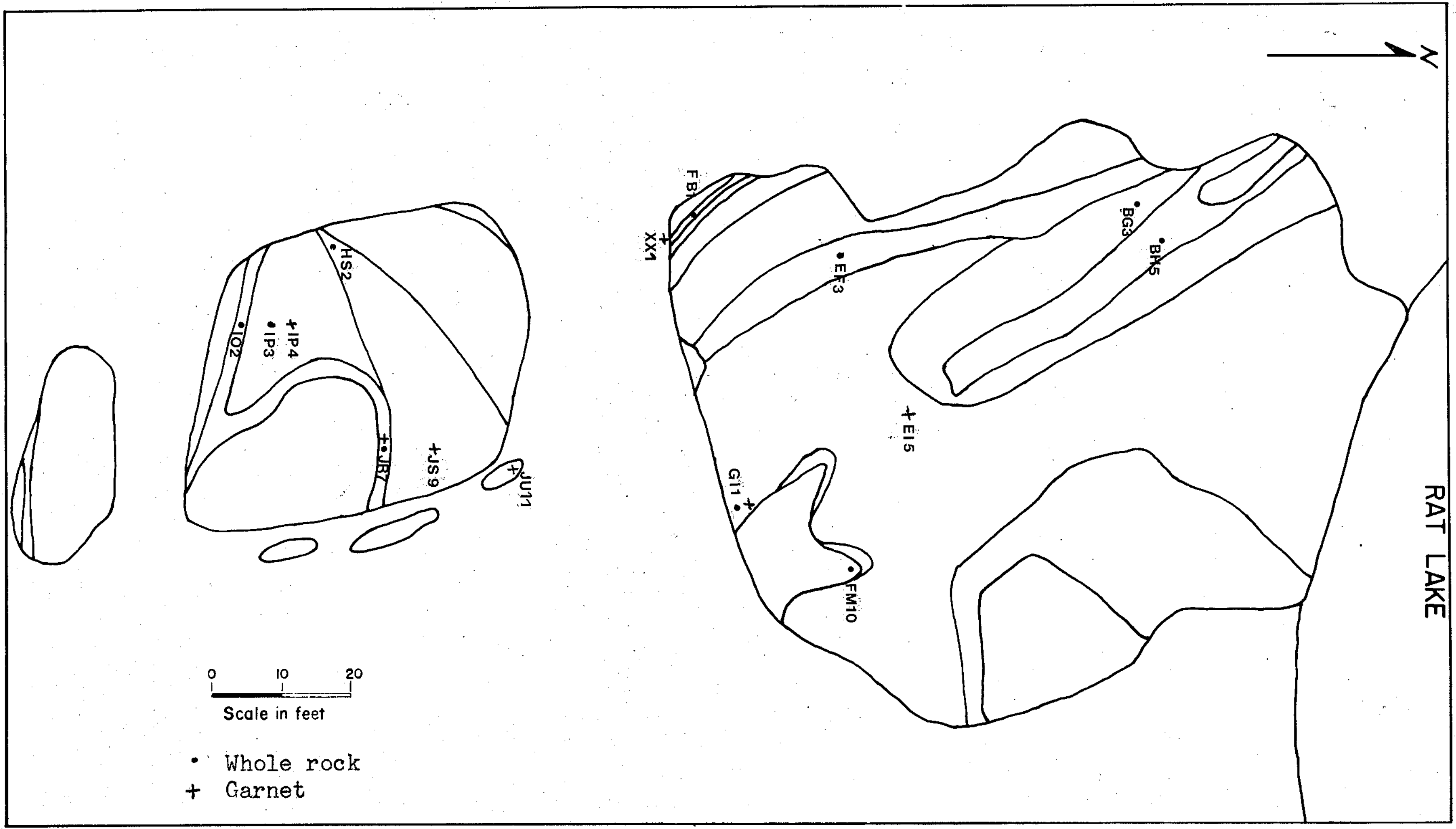

Fig. 12; Location of samples for whole rock and garnet analysis

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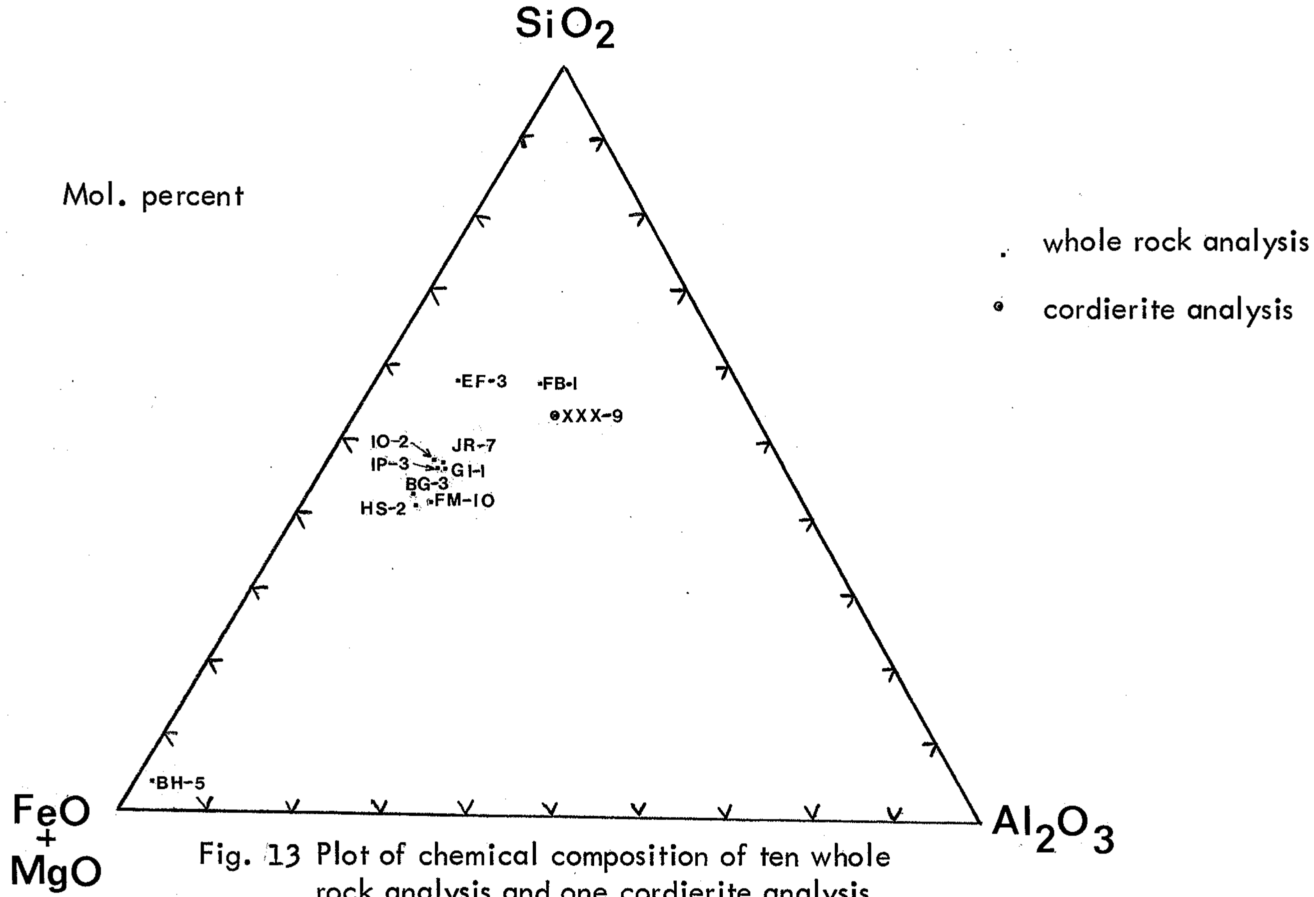

Fig. 13 Plot of chemical composition of ten whole rock analysis and one cordierite analysis.

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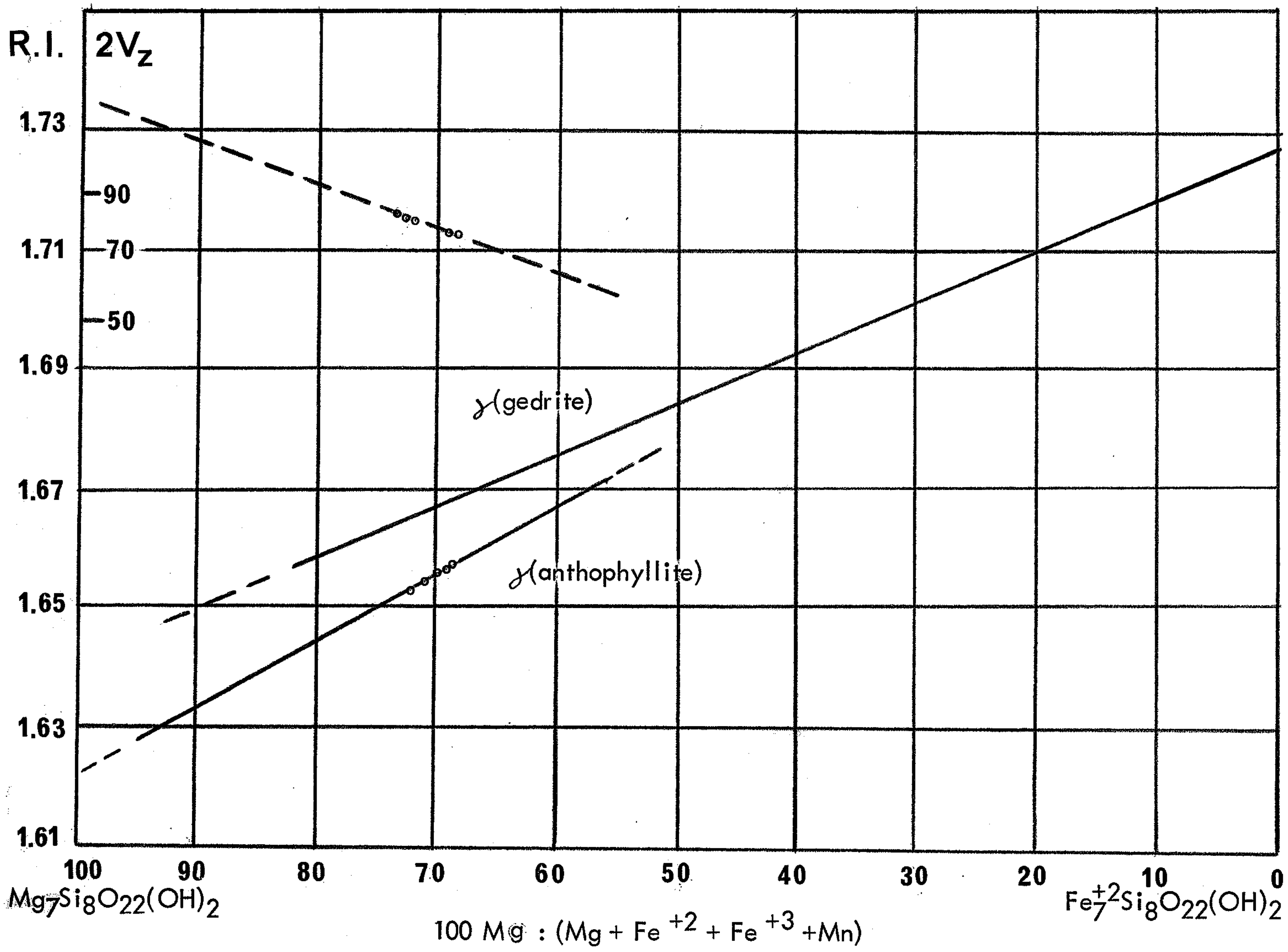

Fig. 14 Relation between the optical properties and chemical composition for anthophyllite. (After Deer, Howie, Zussman, 1966, in An Introduction to the Rock Forming Minerals, Longmans, London.)

TABLE 4

Chemical analysis of Garnet in wt.%

Sample No.	XX-1	IP-4	JR-7	JU-11	EI-5	GI-1	JS-9
SiO_2	37.45	37.15	38.10	38.15	37.15	36.40	36.50
Al_2O_3	20.40	20.36	20.36	20.22	22.72	20.76	20.84
FeO	25.63	24.24	24.60	24.84	25.16	25.02	24.22
CaO	0.00	0.00	0.00	1.34	0.26	0.10	0.40
MgO*	9.43	9.79	8.43	8.70	8.44	10.04	12.49
MnO*	4.25	5.98	4.47	4.01	3.47	4.90	2.85
TOTAL	94.46	97.52	95.96	97.26	97.20	97.22	97.30

* Analysis done by wet method. Other oxides done by X-Ray Fluorescence.

Analyst - M. Whitfield.

Porphyroblasts of garnet are abundant. The garnets range in size from 0.5 mm to 8.o mm in diameter. Crystal faces are not well developed although the euhedral shape is generally preserved. Without exception, the garnets are badly fractured.

Garnet does not show any sign of reaction except in the presence of sillimanite, where the garnet and sillimanite are being replaced by cordierite and hercynite Fig. 15).

Cordierite:

One chemical analysis of cordierite is given in Table 5, and plotted on Fig. 13. The MgO/FeO = 3.4, making this cordierite a very Mg rich variety. The refractive index of two other cordierite samples was similar to that of the chemically analysed sample (Table 5).

A weight loss determination of H_2O was done for sample XXX-9. The weight loss is in accordance with the change in refractive index as described by Schreyer & Yoder, 1964 (Fig. 16). See Appendix 1 for calculation of weight loss.

It may be seen from Fig. 16 that for natural cordierites, high in the MgO component, the determination of H_2O content by mean refractive index is quite accurate.

H_2O content analytically = 2.18 wt.%

H_2O content n_m = 1.90 wt.%

The distortion index of cordierite was measured both before and after heating, it remained the same, i.e. $\Delta = 0.25^{\circ}$, which puts this cordierite in the "low cordierite" field, (Schreyer & Schairer, 1961).

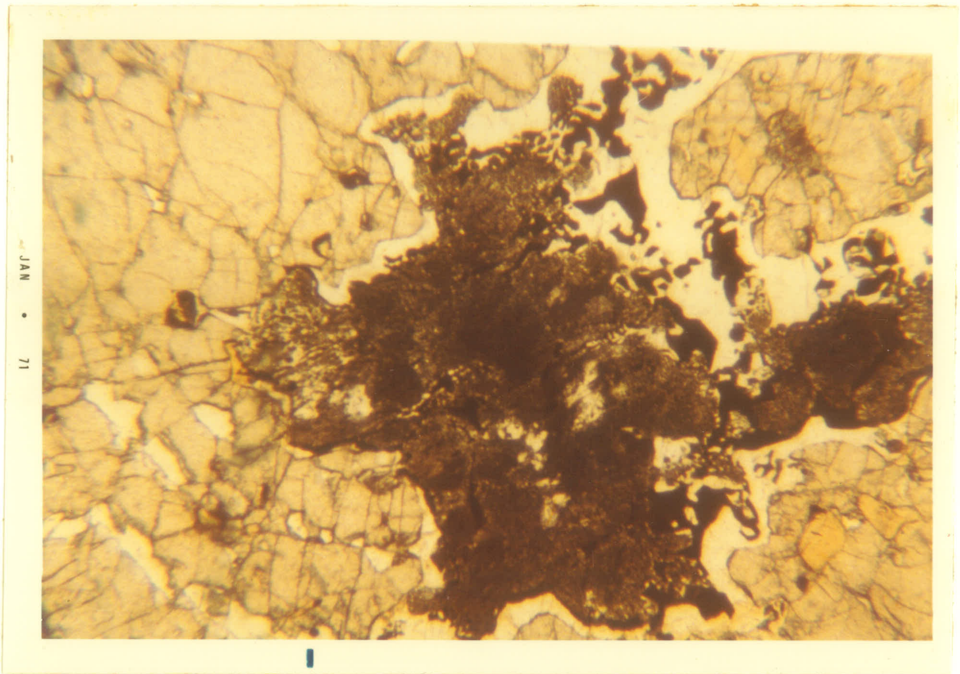

Fig. 15; Sillimanite + garnet → cordierite + hercynite

Sample JP-4. (plane polarized light; X 25)

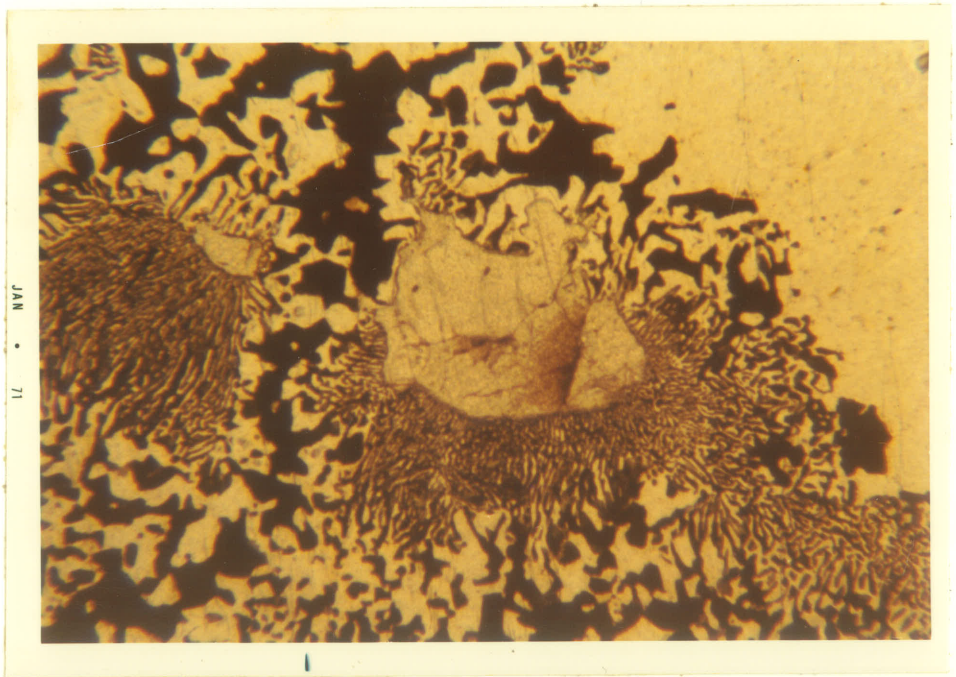

Fig. 15-1 Sillimanite + garnet → cordierite + hercynite (inclusion in garnet). Sample JR-7 (plane polarized light; X 25).

TABLE 5

Chemical analysis and optical properties of cordierite.

Analysis done by X-Ray Fluorescence.

Sample XXX-9

Oxide	Wt.%
MgO	10.92
FeO	5.70
K_2O	0.078
Na_2O	2.90
CaO	0.00
TiO_2	0.00
SiO_2	45.90
Al_2O_3	32.00
H_2O	2.10
Total	99.60

Analyst - K Ramlal

Refractive index of cordierite.

R.I.	XXX-9	JO-2	FI-11
α	1.541	1.538	1.540
γ	1.550	1.548	1.550

$2V = 72^\circ \pm 3^\circ$

α = pale yellow

$\beta = \gamma$ = colorless

$\Delta = 0.25^\circ$

Refractive Index	Before Heating	After Heating
α	1.541	1.528
γ	1.550	1.534

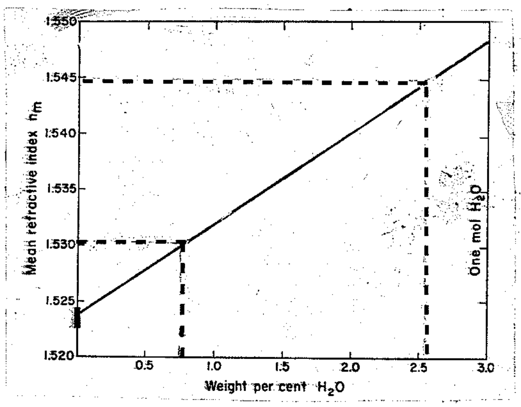

Fig.16 Relationship between water content and mean refractive index. Solid line is for synthetic Mg- cordierites.

The unit cell of cordierite is:

$a_o = 17.086 \pm 0.003$

$b_o = 9.737 \pm 0.002$

$c_o = 9.337 \pm 0.002$

These measurements show that the iron end member makes up 20% of the cordierite (Iiyama 1960). This is in agreement with the MgO/FeO ratio from the chemical analysis Table 5.

The cordierite is optically negative with a 2V of 72°. Of 15 measured crystals 3 have 2V's that deviate from this value but the deviation was never more than ± 3°.

Cordierite in these rocks displayed pleochroism in thick sections only, the formula being:

α = pale yellow

$\beta = \gamma$ = colorless

The cordierite is fresh no alteration, except in one thin section some pinite was noted along fractures in the rocks. Pinite was also present on one large cordierite crystal collected from the surface of the outcrop. Pinite separated from cordierite from sample XX-3 is chlorite plus serpentine (?) (X-Ray diffraction, Appendix II).

Cordierite contains abundant zircon inclusions that have deep yellow pleochroic haloes. It was also noted that short, curved fractures often radiate out from the zircon inclusions into the cordierite.

Many cordierite grains and larger crystals are twinned. This twinning may be polysynthetic or penetration twinning (Fig. 17).

There is no textural evidence of any replacement of cordierite.

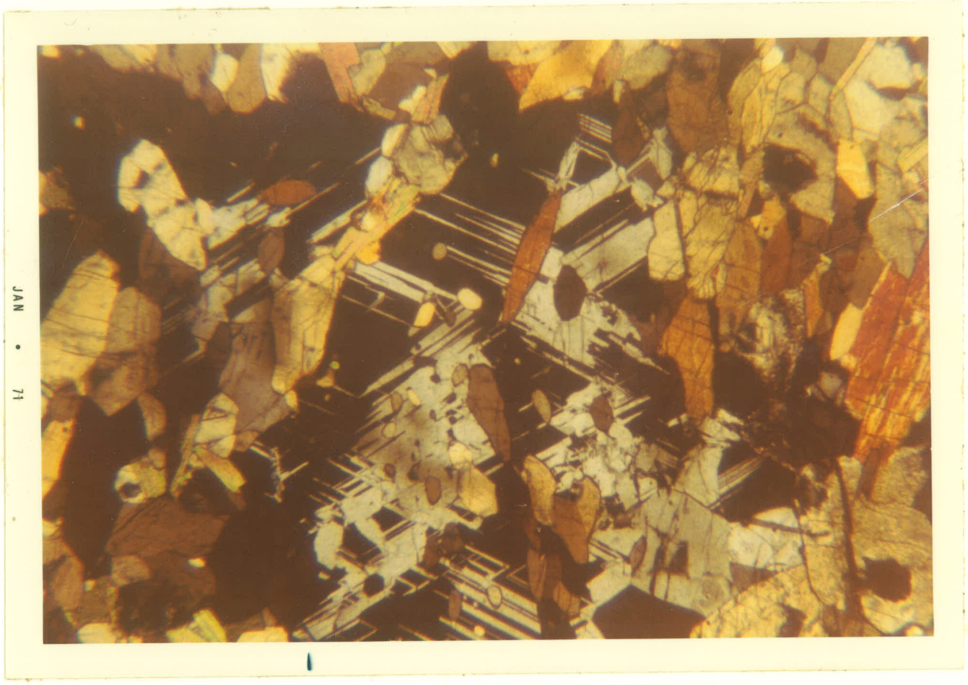

Fig. 17; Twinning in cordierite. Sample CI-8 (X-Nicols; X 25).

Sillimanite:

Sillimanite occurs as colorless, short prismatic crystals and as bundles of fibres.

The 2V varies from 19° to 27° but most grains are 24°.

Sillimanite was a stable mineral phase during the first (highest) grade of metamorphism reached in the area, but reacted with garnet to form cordierite and hercynite during retrograde metamorphism.

Orthopyroxene (hypersthene):

2V = 70 - 90° (range)
α = pink
β = faint yellow
γ = very pale green

Only rare, coroded bits of hypersthene have escaped alteration to anthophyllite.

The pyroxene was stable during the first (highest) grade of metamorphism and is present as a relict phase in the retrograde assemblage.

Magnetite:

Magnetite is present in all rock units except the marginal quartzites. In the rock units, with the exception of magnetite granoblastite (Unit 7), magnetite occurs as sub-euhedral grains. Where it occurs with cordierite, hercynite is always present.

In the magnetite granoblastite, magnetite makes up 90 modal percent of the rock. The magnetite crystals display euhedral outlines. No two crystals of magnetite contact each other along a common grain boundary, there is always a small space between grain boundaries, filled with unidentifiable anisotropic mineral (Fig. 10).

Oxidation of magnetite to hematite is attributed to weathering (hercynite and hematite cannot coexist in equilibrium, Turnock & Eugster, 1962).

Late stage hydrothermal activity introduced carbonate along fractures. Siderite was produced from the magnetite during this activity.

Hercynite:

Hercynite is present in all rock units except the marginal quartzites (units 1 & 4). The amount of hercynite present is dependent upon the extent of reaction between garnet and sillimanite and/or anthophyllite and hercynite.

It has dark green color in plane polarized light. Some exsolution textures were noted between the hercynite and magnetite (Fig. 18). Hercynite is a stable mineral phase in the retrograde assemblage in the presence of cordierite. Where hercynite shares a common main boundary with anthophyllite, neither phase is stable, and cordierite is produced.

Biotite:

Biotite is present with all mineral assemblages. It is present as euhedral crystals studded with abundant zircon inclusions surrounded by haloes. Biotite is pleochroic the formula being:

α = brownish green

$\beta = \gamma$ = dark green

Quartz:

Quartz is absent in the schists, porphyroblastites and granoblastites. It is present in the marginal quartzites where it coexists with sillimanite, cordierite, anthophyllite and biotite. A few garnets may also be present.

Potash feldspar:

This mineral is found only in Unit 13, the coarse-grained cordierite -

garnet - feldspar rock. It occurs as large crystals measuring up to one inch across and is associated with large crystals of cordierite ± porphyroblasts of garnet (Fig. 19).

Plagioclase:

Plagioclase is absent from all assemblages.

A petrographic description of each map unit is given in Appendix III. A sample location map is given in Fig. 20.

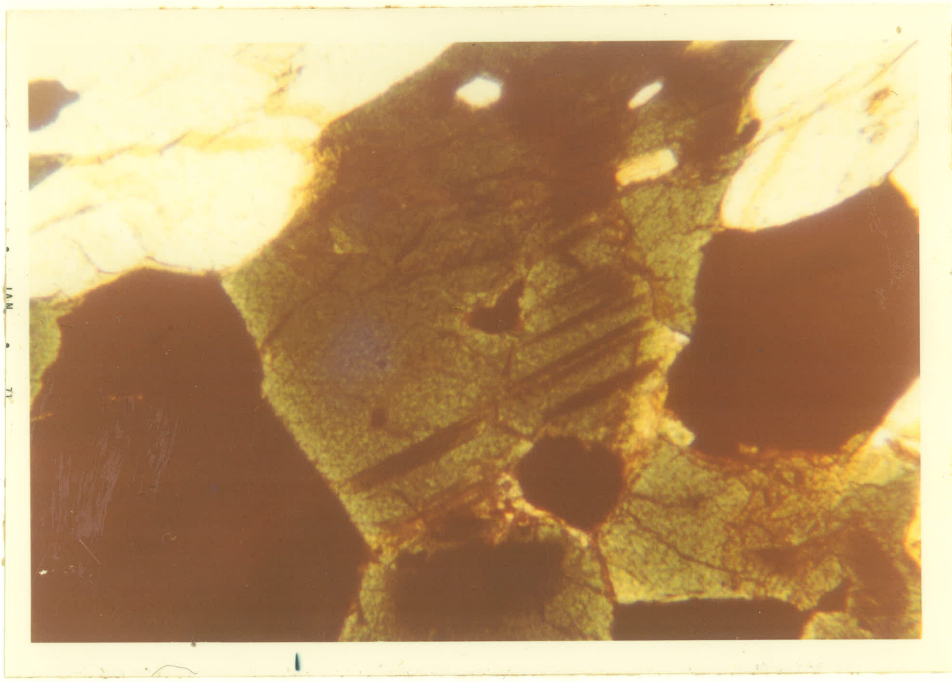

Fig. 18; Exsolution texture between magnetite and hercynite. (plane polarized light; X 100).

Fig. 19; Large potash feldspar crystals associated with cordierite ± garnet in map unit #13.

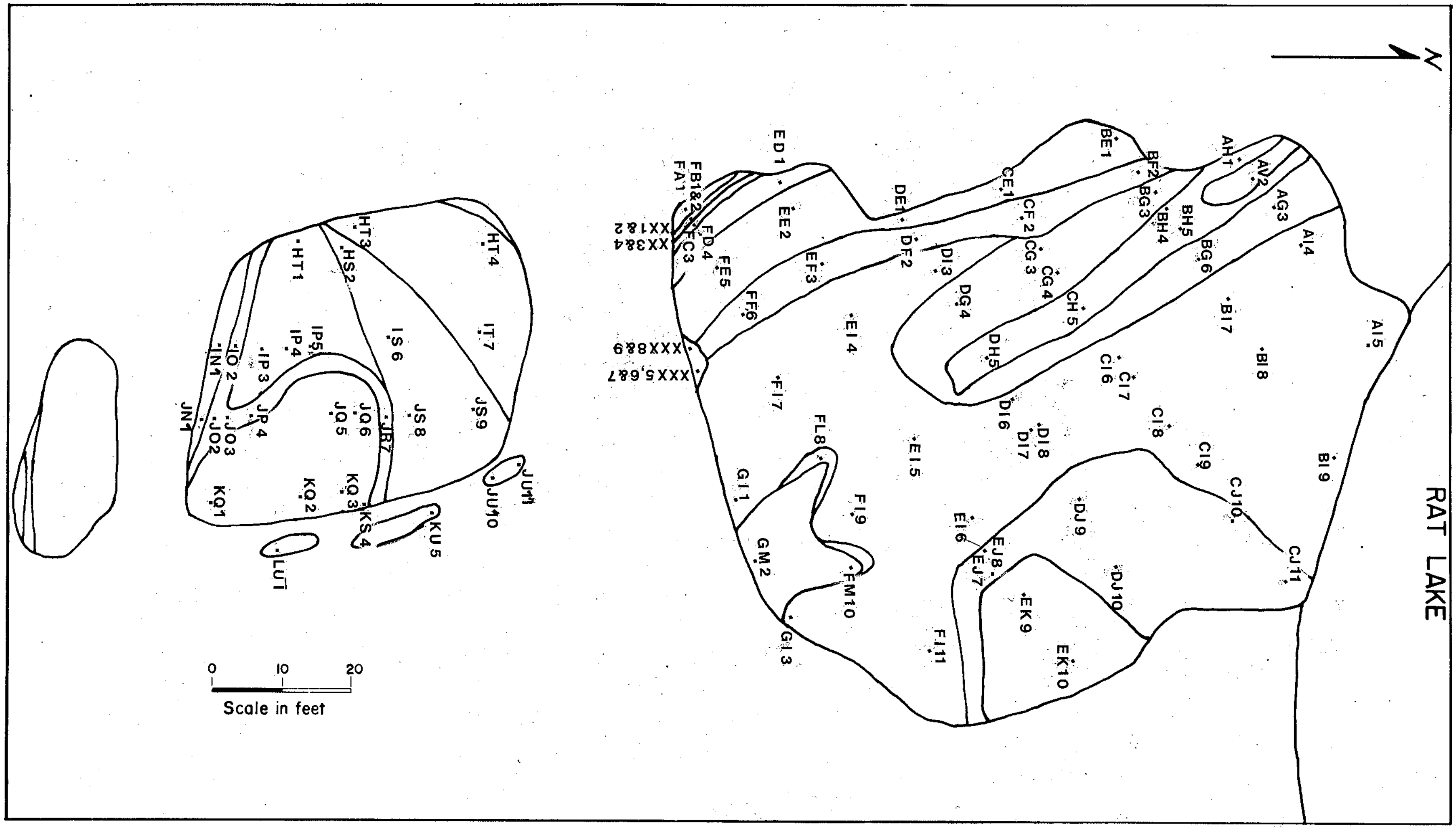

Fig. 20; Sample location map.

CHAPTER V

INTERPRETATION

Metamorphic History and Reactions:

Two stages of metamorphism are recognizable in the rocks, an early granulite facies metamorphism and a later upper amphibolite grade that was retrogressed from the granulite grade.

The mineral assemblage garnet - cordierite - sillimanite - hypersthene indicates a high temperature, moderately high pressure pyroxene granulite grade of metamorphism.

This early granulite facies assemblage has been retrograded to an upper amphibolite grade represented by the assemblage garnet - cordierite - anthophyllite - hercynite. The cordierite - hercynite knots are pseudomorphous after the early garnets if sillimanite is present.

The reactions are:

$$\text{Garnet} + 2\ \text{Sillimanite} \longrightarrow \text{Cordierite} + \text{Hercynite} \qquad (1)$$

$$115.28 + 2(49.91) \qquad\qquad 233.50 + 40.82$$

$$215.10\ \text{cm}^3 \qquad\qquad 274.32\ \text{cm}^3$$

$$\Delta V = +\ 59.22\ \text{cm}^3$$

$$\text{Orthopyroxene} + \text{quartz} + \text{water} \longrightarrow \text{anthophyllite} \qquad (2)$$

$$7(\text{MgFe})\ \text{SiO}_3 + \text{SiO}_2 + \text{H}_2\text{O} \longrightarrow (\text{MgFe})_7\text{Si}_8\text{O}_{22}(\text{OH})_2$$

$$\text{Anthophyllite} + \text{Hercynite} \longrightarrow \text{Cordierite} \qquad (3)$$

Since reaction (2) is a hydration reaction the volume increase must be toward the right hand side of the equation. ΔV for reaction (3) cannot be determined due to the absence of an additional (Fe, Mg) phase.

Reaction (3) involves the removal of FeO and Mgo. There are no other phases present in thin section which could take up these components. However, one possibility does exist. A secondary garnet is present as fracture fillings in map units "11 and 12, (Fig. 24, 25). It may also be possible that the cordierite produced during this reaction is more iron rich than that of reaction (1). The reaction as written states only that anthophyllite and hercynite cannot coexist with common grain boundaries at the lowest grade of metamorphism.

The lower grade of metamorphism (amphibolite facies) could have taken place at temperatures that overlap that of the granulite facies (650°C - 700°C). A decrease in pressure from approximately 4.5 to 3 Kb (Hess, 1969) and hydration by water is all that is necessary. The presence of magnetite and hercynite indicates that the PO_2 was low and constant.

Phase relationships are shown in Fig. 21. From this figure, it can be seen that the garnet - sillimanite tie line of the granulite facies is broken by the cordierite - hercynite tie line during amphibolite facies (retrograde) metamorphism.

Origin of the Rocks:

The chemistry of these rocks best fits that of a residual clay derived from a basic igneous rock (Table 1). Although there is not exact correspondence between the analyses done for this study and those given for comparison, it is proposed that the anthophyllite - garnet - cordierite rock originated as an iron-rich residual clay. The absence of CaO and alkali rules out the possibility of metamorphism of an igneous rock without metasomatism.

In the Granville Lake area, approximately 35 miles N.W. of Rat Lake, Campbell (1971) shows that the unconformity between the Sickle and Wasekwan series is marked by a conglomerate lying at the base of the Sickle series. To the east of Granville Lake the conglomerate pinches out and an amphibolite marks the base of the series. The position of this unconformity in the Rat Lake area should then fall at the contact of the pelitic gneisses and the quartzo-feldspathic gneisses. It is at this stratigraphic horizon that the anthophyllite - garnet - cordierite rocks occur. This substantiates the possibility of these rocks being a weathered deposit.

The leaching of CaO from basic igneous rocks could produce the present chemistry of the anthophyllite - garnet - cordierite rocks. Since these rocks are unique in the Rat Lake and Mynarski Lakes areas, and their chemistry does not match that of a sediment, a second possible origin is that of a metasomatized basic or ultrabasic rock. Taylor (1971) has recognized pillows in the Mynarski Lakes area lying at approximately the stratigraphic level (the amphibolite) as the anthophyllite - cordierite - garnet rocks at Rat Lake.

Robertson (1953) describes an "Anthophyllite Band" from the Batty Lake Area, Manitoba. This map unit is continuous for approximately eleven miles along strike and shows strict stratigraphic control. The characteristic mineral assemblages are:

1. Anthophyllite - cummingtonite - biotite;
2. Anthophyllite - biotite - almandine;
3. Anthophyllite - cordierite - biotite;
4. Anthophyllite - cordierite - biotite - almandine.

Quartz and plagioclase are minor constituents and magnetite - spinel intergrowths have been noted. The iron content of anthophyllite increases to the east, along with the appearance of cordierite and magnetite. Robertson favors iron-magnesium metasomatism of an aluminum rich tuff to produce the assemblages and account for the lateral extent of the unit.

The similar exposure at Rat Lake does not have any extension along strike and quartz and plagioclase are absent from the assemblages. It is for these reasons that the anthophyllite rocks at Rat Lake are not considered to have a similar origin as those at Batty Lake.

Metasomatic processes such as those in models put forth by Orville (1969) and Vidale (1969) may have taken place in these rocks of unusual composition. This is only speculation, since no conclusive evidence of cation migration was seen in these rocks.

The abundance of cordierite in these rocks is in agreement with the chemical control discribed by Wynne Edwards and Hay (1963) -

> "...cordierite is thus a stable phase in high grade regional metamorphism, but is found in lime-poor, magnesium-rich rocks that are less common than those with compositions falling in the stability field of garnet...".

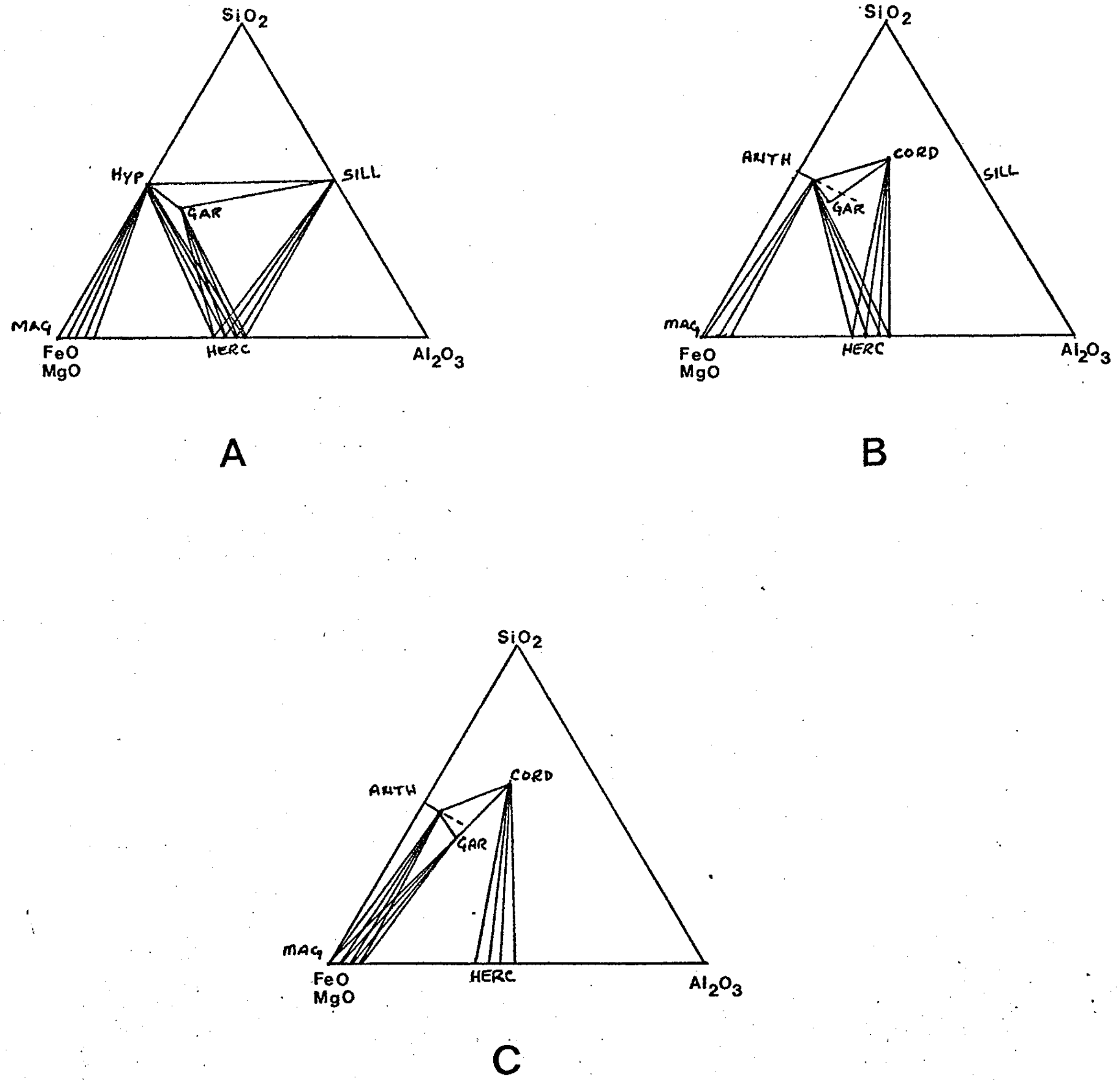

Fig. 21; A. Phase relationships of pyroxene granulite grade metamorphism.

B. Phase relationships of upper amphibolite grade metamorphism showing the Garnet - sillimanite tie line has been cut by cordierite - hercynite tie line.

C. Phase relationship of upper amphibolite grade metamorphism showing the anthophyllite - hercynite tie line has been cut by a garnet - magnetite tie line.

APPENDIX I

Weight Loss of Cordierite

Sample of cordierite heated at 794° for a duration of 12 hours at 1 atm. pressure.

The Pt foil enveloped was pre-heated to drive off any moisture that might be on the foil

1. Before heating at 794° C

   Weight of Pt enveloped pre-heated = 0.63294 gm

   Weight of Pt enveloped pre-heated + sample = 1.58041 gm

   Weight of sample 0.84747 gm

2. After heating at 794° C

   Weight of Pt envelope + sample = 1.56204 gm

   Weight lost due to heating (H_2O) = 0.01837 gm

$$\frac{184}{8475} = 2.18\%$$

APPENDIX II

Pinite alteration after cordierite. X-Ray powder determination.

Film #A-1788 X-Ray laboratory, University of Manitoba.

14.00 Å - very weak

7.80 - very weak

7.00 - Strong

4.45 - weak

3.85 - very weak

3.50 - strong

3.35 - weak

2.90 - weak

2.65 - very weak

2.58 - strong

2.45 - very weak

2.35 - very weak

2.10 - very weak

1.86 - weak

1.70 - weak

1.66 - weak

1.60 - strong

1.54 - strong

1.44 - weak

1.41 - weak

APPENDIX III

Petrographic Description of Map Units

1. Biotite quartzite: Quartz makes up 85 modal percent of the rock. Anthophyllite, sillimanite and biotite make up the remaining 15 modal percent of the rock. Anthophyllite, sillimanite and biotite all occur as small, short euhedral crystals as inclusions in quartz grains. The quartz grains form a granoblastic mosaic.

2. Cordierite - Garnet - Biotite schists; Quartz plus cordierite make up 65 modal percent of the rock, biotite 25%, sillimanite 10%, garnet 5% hercynite and anthophyllite are present in trace amounts. The platy allignment of biotite gives the rock its schistose fabric. The sillimanite occurs as short prismatic crystals in clusters and as fibrolite.

The cordierite is generally interstitial to the quartz and the two minerals are present in about equal amounts.

The garnet is porphyroblastic and is inclusion free.

3. Banded Cordierite - Biotite schists: Quartz and cordierite comprise 50 modal percent of the rock, biotite 30% and anthophyllite 20%. There is a faint alternation between light and dark layers in the rock which may reflect primary layering. The alignment of the biotite plates gives the rock its schistose texture. The quartz and cordierite form a medium grained mosaic.

Anthophyllite occurs as well developed euhedral crystals that are aligned parallel to the biotite schistosity and therefore amplify the schistose texture.

The biotite is the green variety and is studded with zircon inclusions.

4. Amphibole - Garnet quartzite: Quartz is present as 60 modal percent of the rock. Cordierite is generally present making up 10% of the rock. Anthophyllite can make up to 20% of the rock while the remaining 10% is made up of garnet, sillimanite, biotite and trace magnetite. This modal description is the average from four thin sections and hand specimen inspection. The modal percent of anthophyllite varies between slides from 0% to 50% while that of biotite varies from approximately 2% to 25%. The rock in hand specimen does not reflect these variations. The reason for these variations within the map unit is not understood. Biotite, Anthophyllite and sillimanite occurs as euhedral crystals clustered together to form very thin layers or lenses in the light coloured material.

5. Garnet - Cordierite - Amphibole schists: The 60 to 70 modal percent of anthophyllite makes up the bulk of this map unit. Cordierite is present in the amount of 15 modal percent the rest being made up of biotite and garnet. Magnetite and hercynite may be present in trace amounts or may be absent all together.

Garnets are porphyroblasts that show an inclusion free core with a rim of amphibole and biotite inclusions. Inclusions of a colorless mineral are sometimes present. Because of the small size of these inclusions it is impossible to determine whether they are quartz or cordierite.

The cordierite is pitted with inclusions of what is probably quartz. Zircon inclusions are always present.

The biotite is green in colour. Generally it displays good euhedral outlines, but in a few cases appears corroded. This corroded biotite has a lower birefringence than the uncorroded variety. Some biotite appears to be replacing amphibole. The anthophyllite is as good euhedral crystals. Many end sections show excellent amphibole cleavage. The parallel allignment of this mineral gives the rock a schistose and lineated texture.

6. Magnetite - Amphibole porphyroblastite: Anthophyllite makes up 80 modal percent of the rock. Magnetite and hercynite combined, contribute 10 modal percent. Biotite and pyroxene in equal amounts make up the remaining 10 percent.

The orthoamphibole has a radiating habit. Pyroxene generally forms the nucleus of this radiating habit of the amphibole. Biotite can also be present at the grain boundaries of the nucleus pyroxene. Some of the biotite appears to have patchy chlorite associated with it.

7. Magnetite granoblastite: Magnetite makes up 90 modal percent of this rock. Pyroxene and biotite make up the remaining 10%. Hercynite is present but does not contribute more than 1% to the modal distribution.

8. Cordierite - Garnet - Amphibole porphyroblastite: Thin section modal analysis of this rock is not satisfactory due to the unequal distribution of the garnets over the exposed outcrop of this map unit, (Fig. 22). In outcrop, garnets make up about 25% of the exposure, cordierite 10 to 15% and anthophyllite 60 to 65%.

The garnets are porphyroblasts and are badly fractured. Some garnets are free of inclusions while others have inclusions plus a reaction rim. Cordierite occurs as knots and eliptical lenses. Cordierite contains zircon inclusions and generally has hercynite associated with it. Cordierite can also occur interstitially to the amphibole. Anthophyllite occurs in two forms. Well developed euhedral crystals,

Fig. 22; Cordierite - garnet - anthophyllite porphyroblastite showing unequal distribution of the garnets.

many showing excellent end sections are more abundant than anthophyllite displaying radial growth. The anthophyllite ground mass does not appear to be bent around the garnet prophyroblasts. Two exceptions have been noted but biotite plays a role in these two cases.

Biotite is often present up to 15% in the ground mass. Where biotite contacts a garnet, the biotite can be bent around the garnet but usually as in the case of the amphibole, the biotite terminates at the garnet boundary or at the reaction rim surrounding the garnet. The biotite in these rocks is always green in colour and contain zircon inclusions.

Magnetite is associated with the amphibole while the hercynite is associated with the cordierite.

9. Spheroidal Magnetite - Garnet - Amphibole porphyroblastite: This map unit is very much like the "Cordierite = Garnet - Amphibole porphyroblastite" except for the amount of magnetite present and its texture.

The magnetite can make up to 20% of the rock and it occurs as spheres. The spheres are nearly round. Some show elongation in strike direction, (Fig. 23).

The amount of garnet in this rock is no more than 10% and the garnets occur as small porphyroblasts. Cordierite is present and has hercynite associated with it.

Anthophyllite makes up the greater part of the rock.

10. Magnetite Amphibolite: Magnetite makes up 30% of the rock. Anthophyllite makes up the remaining 70%. Cordierite is present in trace amounts and garnet is absent.

Magnetite occurs as prophyroblasts and as individual grains in the anthophyllite ground mass.

The anthophyllite has a radial crystal growth but no pyroxene has been seen in the cores of the radial habit.

11. Magnetite - Garnet - Amphibole porphyroblastite: This map unit is identical in mineralogy to the "Spheroidal Magnetite - Garnet - Amphibole porphyroblastite". The difference between the two rocks is the texture. This map unit has no magnetite spheres. Garnets have a porphyroblastic habit and are large compared to those of Unit #9, (see Plate 1).

Cordierite is present but not abundant.

12. Magnetite - Biotite - Amphibole granoblastite: Anthophyllite makes up 60 modal percent of this map unit.Magnetite is disseminated throughout the rock. On weathered surface, the rock has a pebbly texture, the silicates are weathered out, leaving the magnetite raised slightly above the outcrop surface. Fractures are filled with garnet, (Fig. 24). Some garnets have a magnetite a core, (Fig. 25).

In thin section, pyroxene forms the nucleus of radiating anthophyllite crystal growth.

13. Cordierite - Garnet - Feldspar rock (very coarse grained): The cordierite and feldspar crystals are very large measuring from 1/2" to 3 or 4 inches across. The garnets are small and make up approximately 2% of the rock.

14. Altered Magnetite porphyroblastite: This map unit is equivalent to Unit 6 except that the rock has been highly weathered, the biotite has a pale yellowish colour in hand specimen.

Fig. 23; Magnetite spheres (porphyroblasts) in radiating amphibole groundmass.

Fig. 24; Garnet filling the fractures in map unit #12

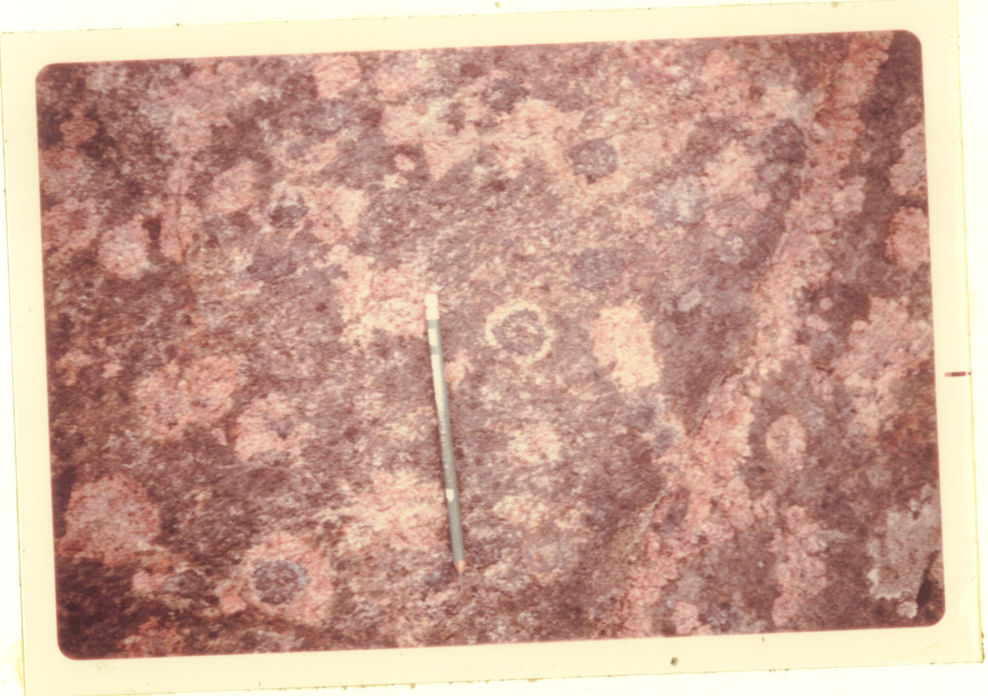

Fig. 25; Garnet rims around a magnetite core map unit #12.

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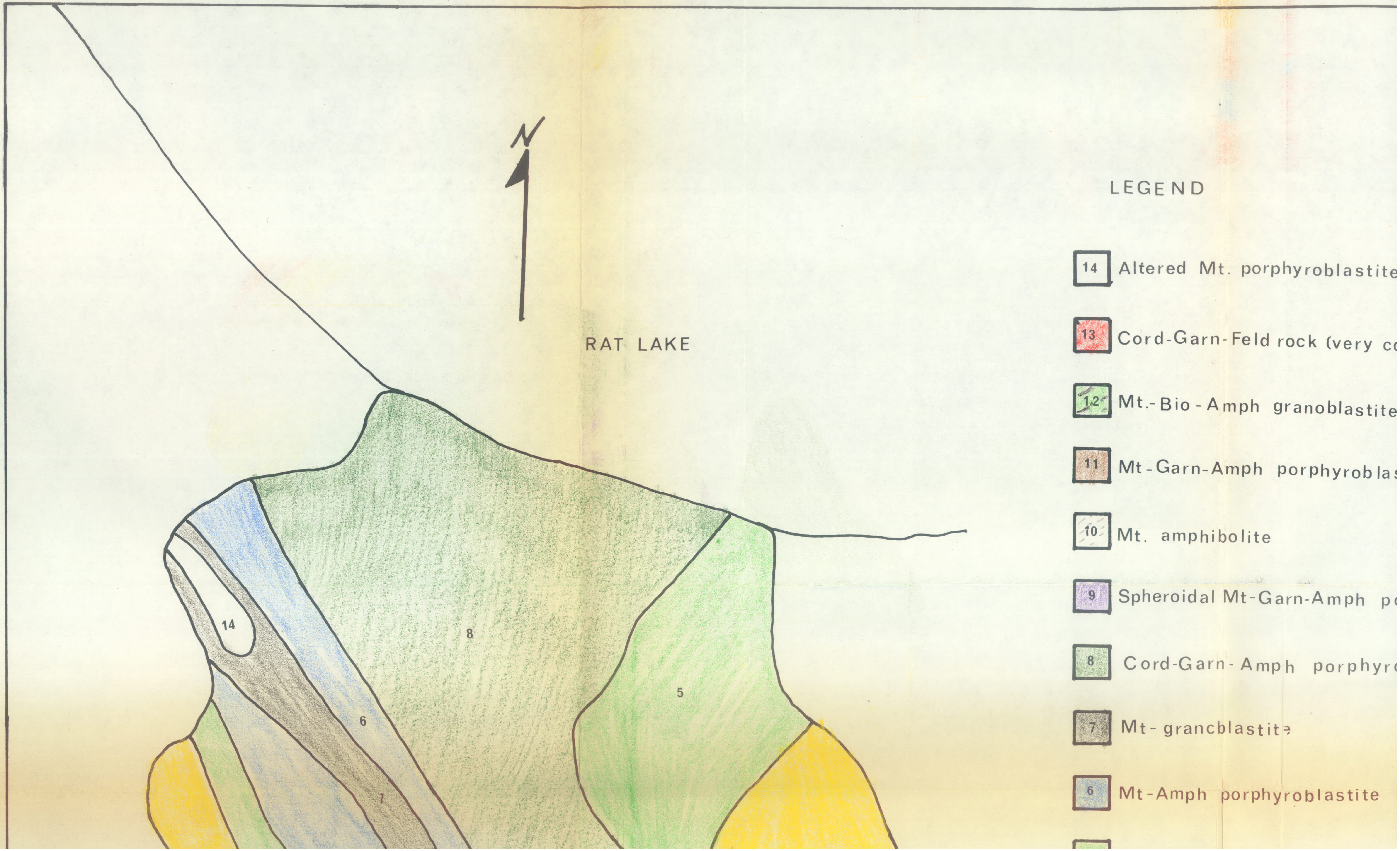
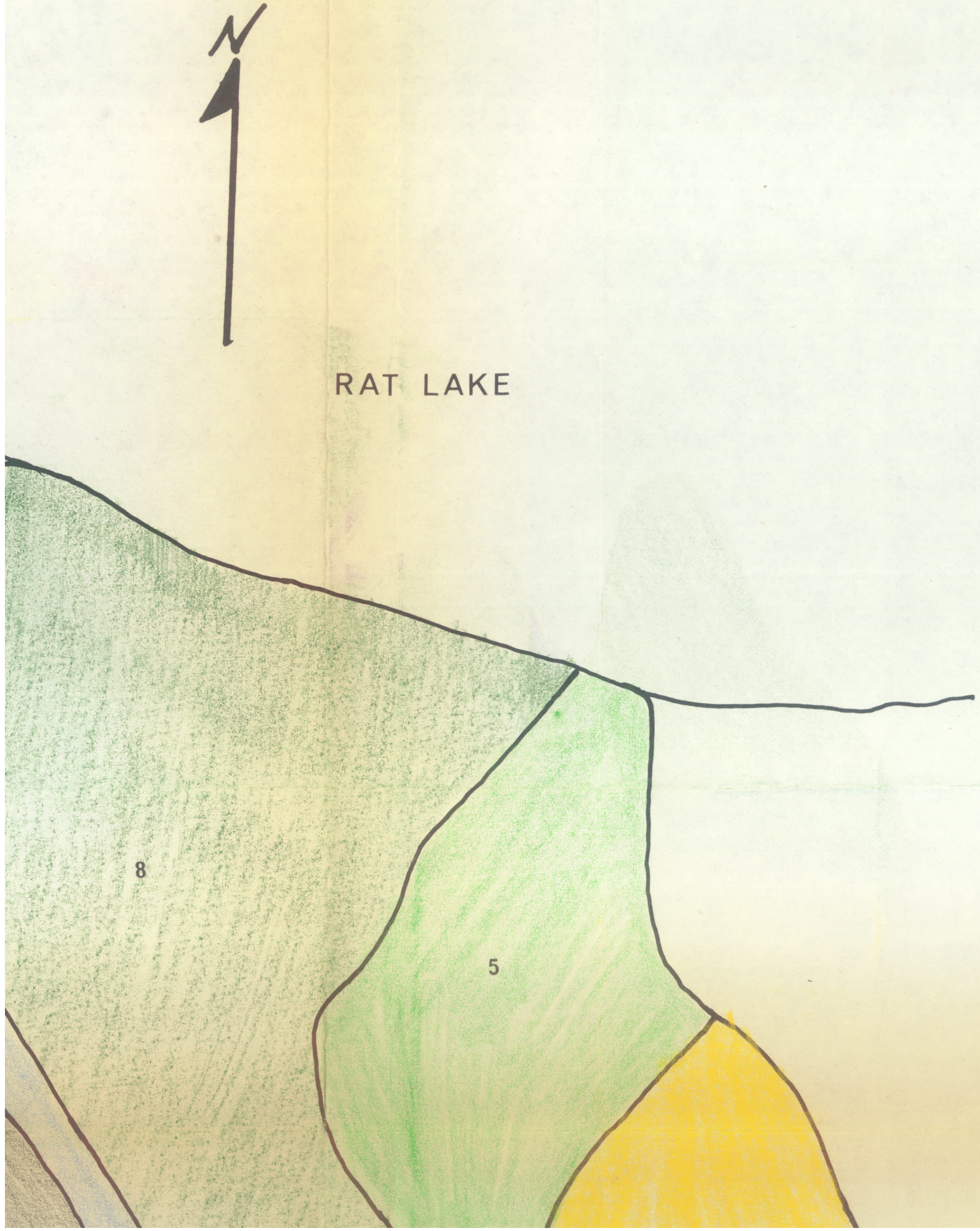
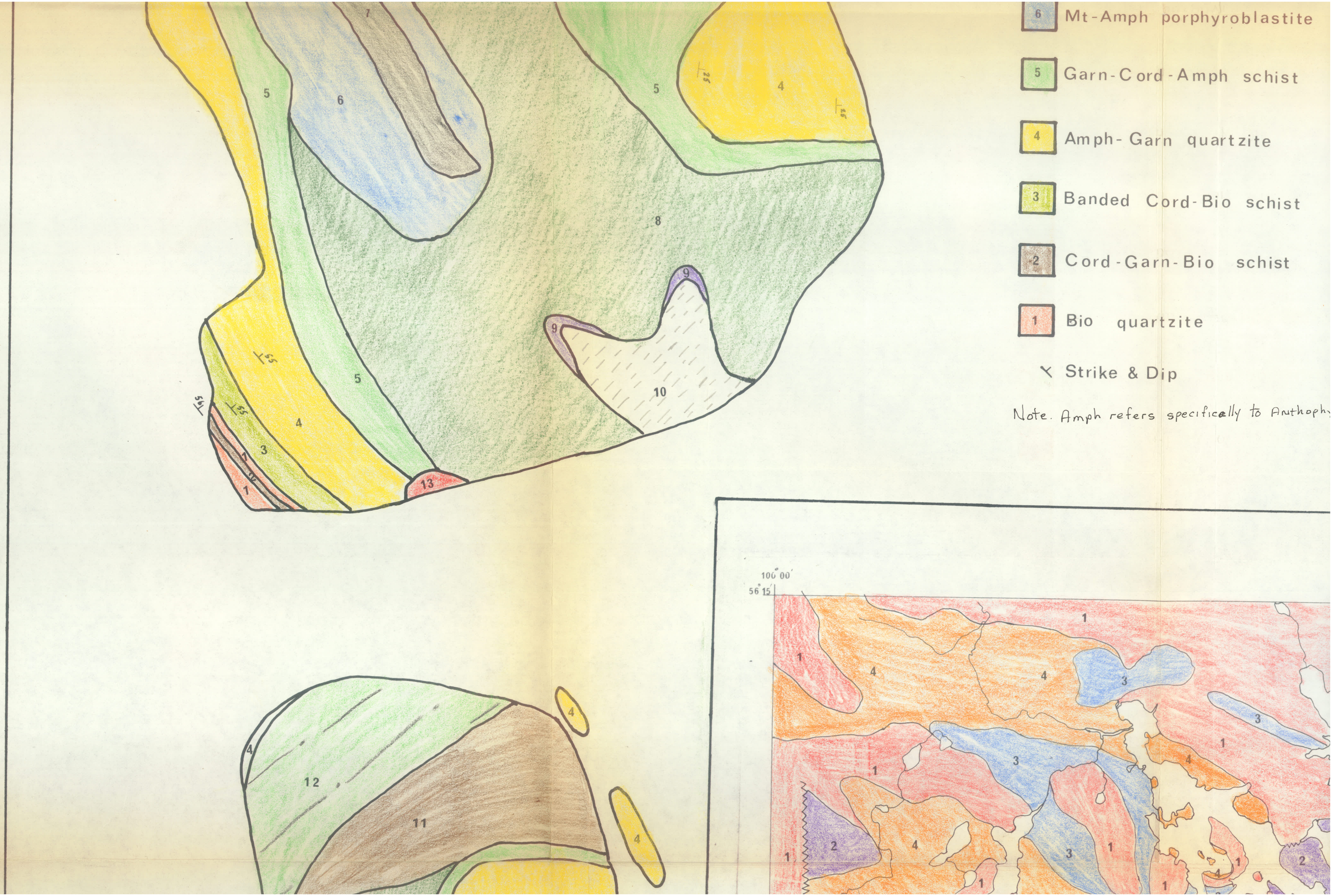

N
RAT LAKE
14
8
5
6
7
LEGEND
14 Altered Mt. porphyroblastite
13 Cord-Garn-Feld rock (very co
12 Mt.-Bio-Amph granoblastite
11 Mt-Garn-Amph porphyroblas
10 Mt. amphibolite
9 Spheroidal Mt-Garn-Amph p
8 Cord-Garn-Amph porphyr
7 Mt-grancblastite
6 Mt-Amph porphyroblastite



LEGEND

14	Altered Mt. porphyroblastite
13	Cord-Garn-Feld rock (very coarse grained)
12	Mt.-Bio-Amph granoblastite
11	Mt-Garn-Amph porphyroblastite
10	Mt. amphibolite
9	Spheroidal Mt-Garn-Amph porphyroblastite
8	Cord-Garn-Amph porphyroblastite
7	Mt- grancblastite
6	Mt-Amph porphyroblastite



6 Mt-Amph porphyroblastite

5 Garn-Cord-Amph schist

4 Amph-Garn quartzite

3 Banded Cord-Bio schist

2 Cord-Garn-Bio schist

1 Bio quartzite

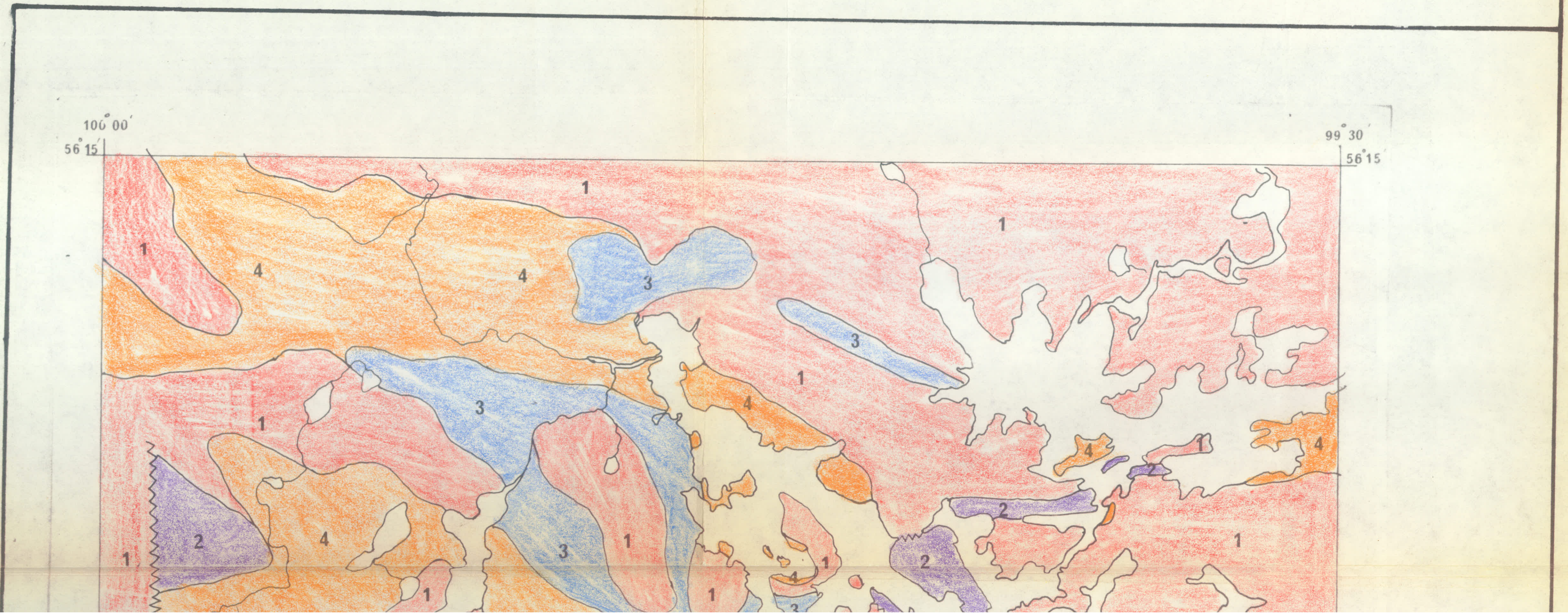
Strike & Dip

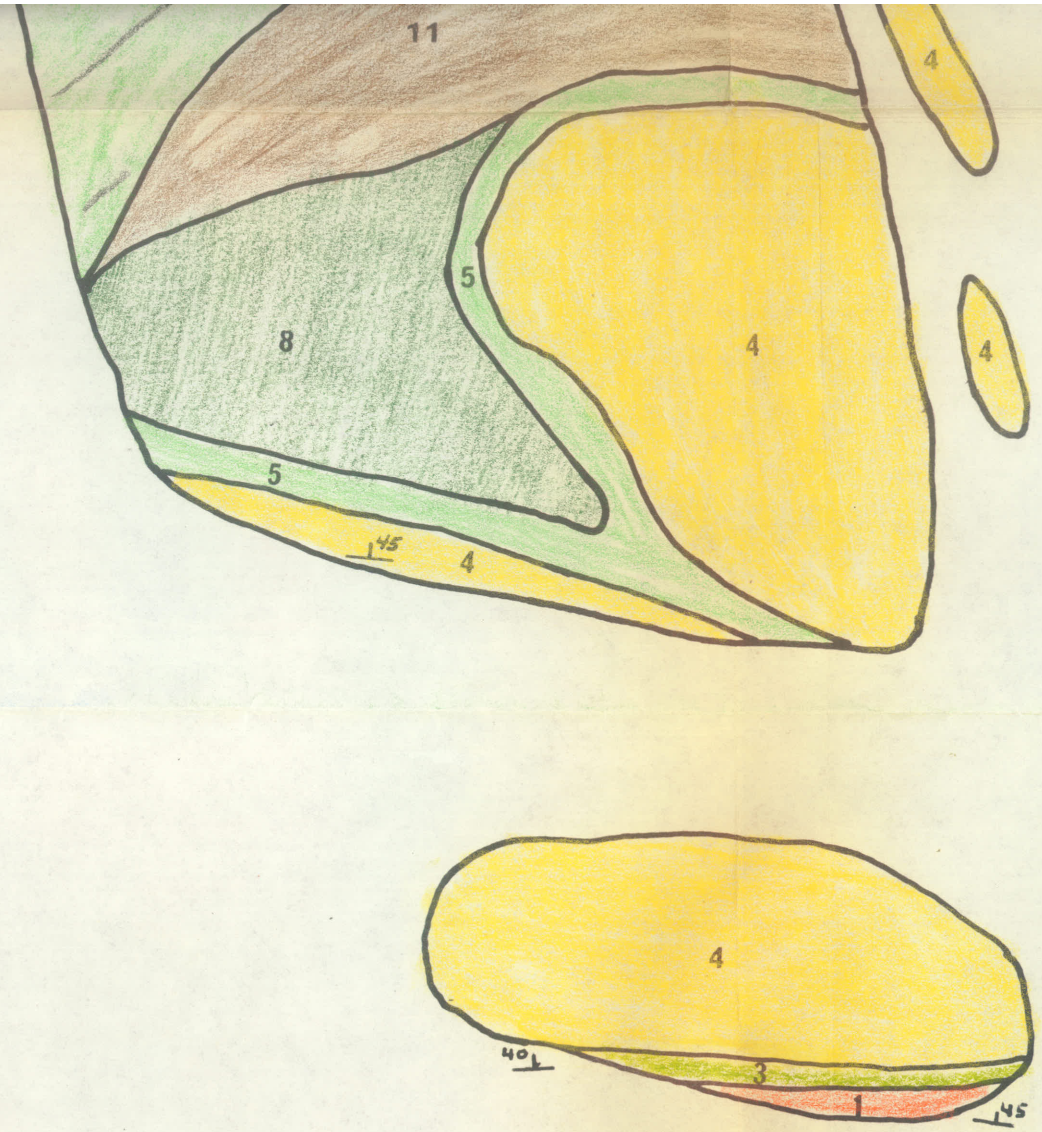
Note. Amph refers specifically to Anthophy

6	Mt-Amph porphyroblastite
5	Garn-Cord-Amph schist
4	Amph-Garn quartzite
3	Banded Cord-Bio schist
2	Cord-Garn-Bio schist
1	Bio quartzite

Ⲭ Strike & Dip

Note. Amph refers specifically to Anthophyllite.



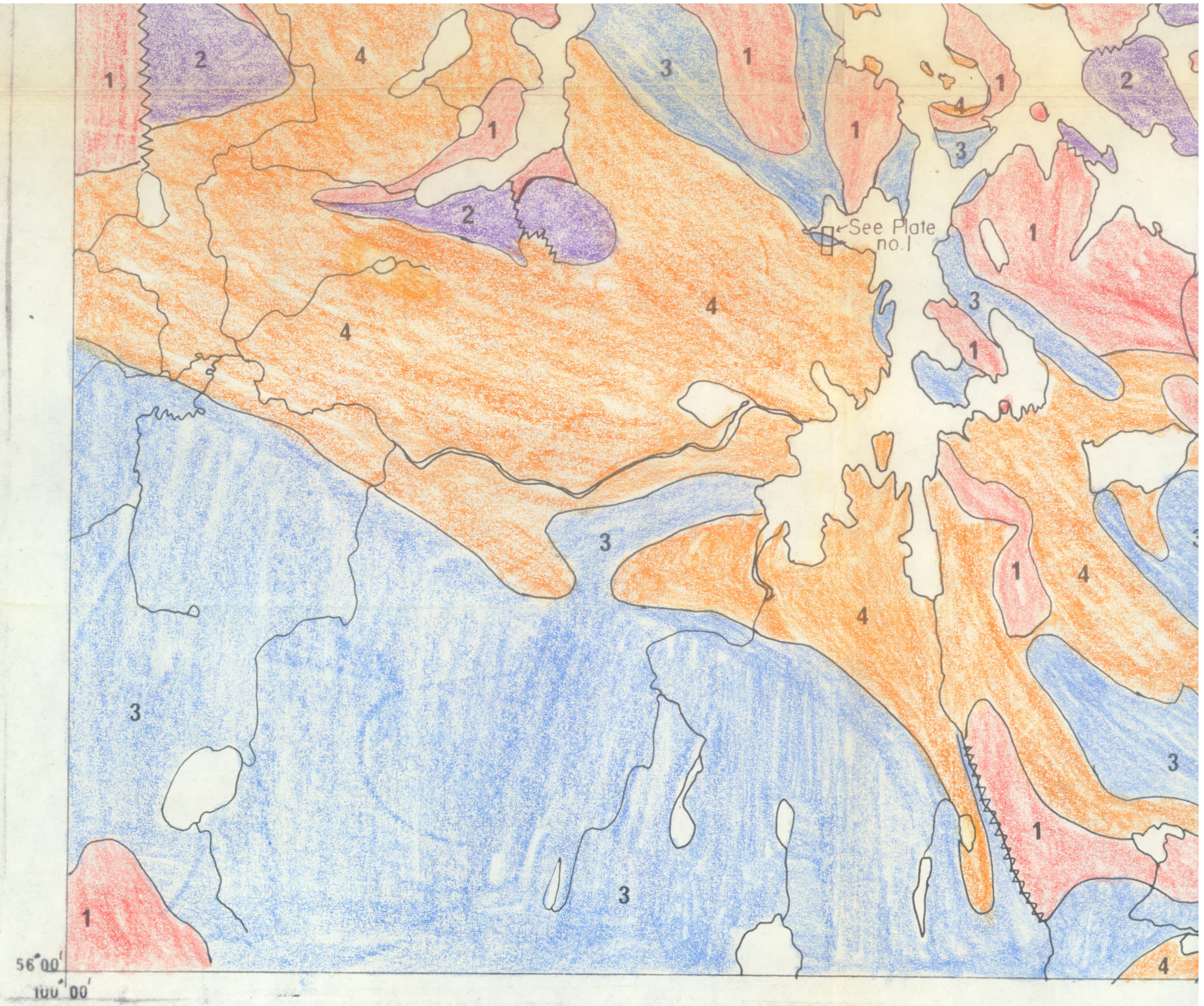


Anthophyllite–garnet–cordierite rocks at Rat Lake Manitoba

0 10 20 30

SCALE
1"=10 Feet

PLATE NO.1



Legend

4 Quartzo feldspathic gneiss

3 Pelitic gneiss

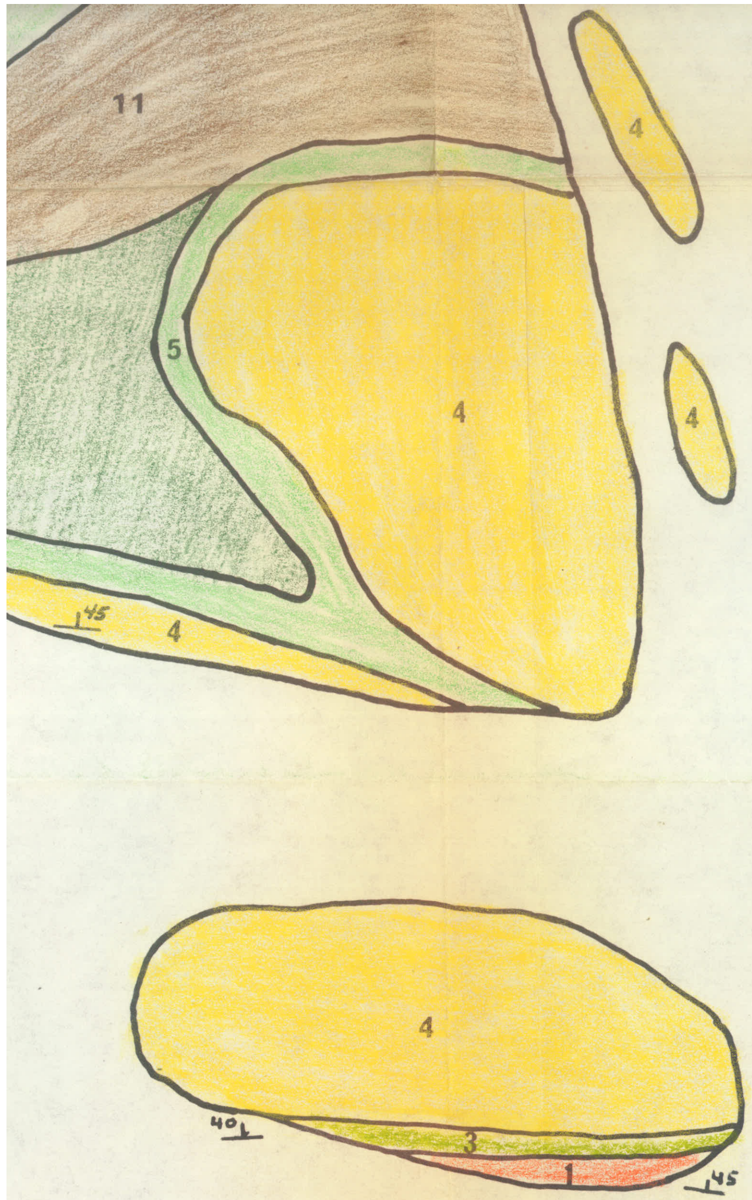
INTRUSIVE ROCKS

2 Granodiorite & Quartz d

1 Tonalite, Monzonite, & M

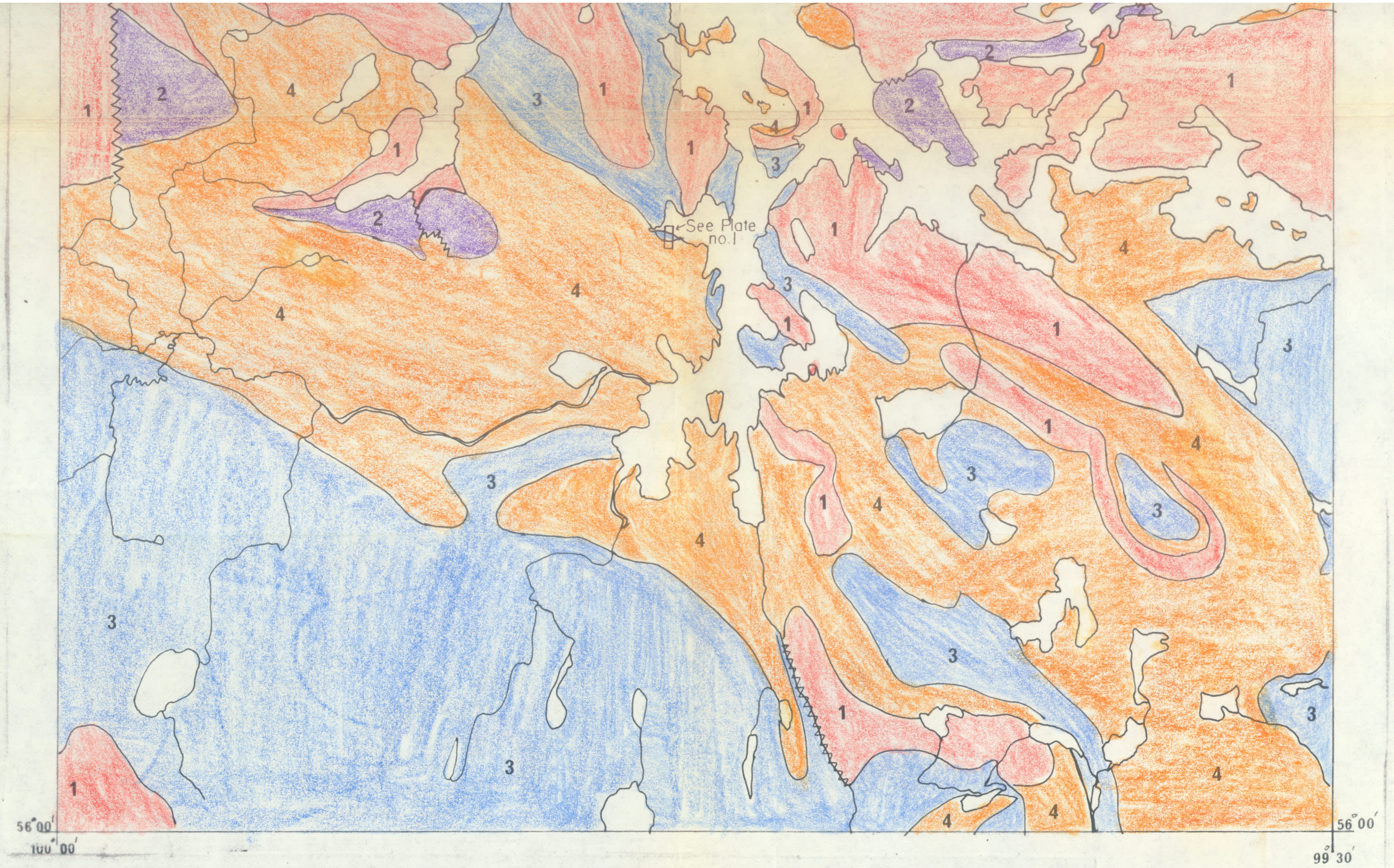
∿∿ Fault

LOCATION & GEOLOGIC MAP OF RAT LAKE –



rocks at Rat Lake Manitoba

SCALE
1"=10 Feet



Legend

4 Quartzo feldspathic gneiss

3 Pelitic gneiss

INTRUSIVE ROCKS

2 Granodiorite & Quartz diorite

1 Tonalite, Monzonite, & Microcline Granite

∿ Fault

0 1 2
Scale in miles

LOCATION & GEOLOGIC MAP OF RAT LAKE - MANITOBA