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FENITIZATION AROUND HEMATITE OCCURRENCES
AT THE HAYCOCK MINE,
HULL AND TEMPLETON TOWNSHIPS, QUEBEC

by

Pierre Lapointe

A thesis submitted to the School of Graduate Studies
in partial fulfillment of the requirements for the
degree of M.Sc. in Geology

University of Ottawa
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UNIVERSITE D'OTTAWA / UNIVERSITY OF OTTAWA
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Title of thesis FENITIZATION AROUND HEMATITE OCCURRENCES AT THE HAYCOCK MINE, HULL AND TEMPLETON TOWNSHIPS, QUEBEC .

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We, the undersigned, certify that we have approved this thesis and that the candidate has defended it successfully.

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ABSTRACT

The Haycock iron-alkalic rocks are members of a series of deposits extending from near Gatineau, Quebec, for 16 km in a northeasterly direction, approximately parallel to the regional trend formed by the metasedimentary rocks. The hostrock is Precambrian biotite gneiss, and phlogopite in the Haycock hematite occurrences gives a Grenvillian K-Ar age. Individually deposits are small, the largest being a mass of solid hematite-magnetite 20 metres long and about 1 metre wide maximum.

Petrological study indicates a typical occurrence can be divided into three concentric zones. The core zone is characterized by hematite-magnetite, the inner zone by aegirine, eckermannite and phlogopite and the outer zone by phlogopite and aegirine.

The Haycock iron-alkalic rocks believed to represent assemblages of minerals formed during metamorphism at low to medium temperature metamorphism at moderate depth by recombination of elements already present in the rock but perhaps with a limited migration (inward) of sodium, magnesium and titanium. Hematite-aegirine deposits are now located in pre-existing iron-rich, stratabound horizons.

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CHAPTER 1

INTRODUCTION

1.1 General Statement

The Ottawa-Hull region contains several bodies of alkalic rock. For example, along the Hull-Templeton township line there are hematite-magnetite deposits associated with alkalic magnesian gneiss (Fig. 1, localities 2 and 3), with the Haycock Mine area (3) containing the largest iron-oxide bodies and alkalic zones. Other alkalic rocks in the area are Meach Lake-McCloskey's Field (1), Viau's Lot (2), Flynn's Lot (4), Rainville Creek (5), Little Dam Lake (6) and Francon Quarry (7). They are shown on Figs. 1 and 5 and will be mentioned later in the text.

This study will be concerned with rocks and minerals characterizing the alkalic zones of the Haycock iron deposits. Coexisting mineral phases will be studied in an attempt to evaluate PTX conditions in order to determine geochemical processes involved in the origin of these rocks. Finally, relationships with other alkalic complexes will be discussed.

1.2 Location and Access

The study area is 16 kilometres (km) northeast of Hull, Quebec and covers 24 square km. The Hull-Templeton

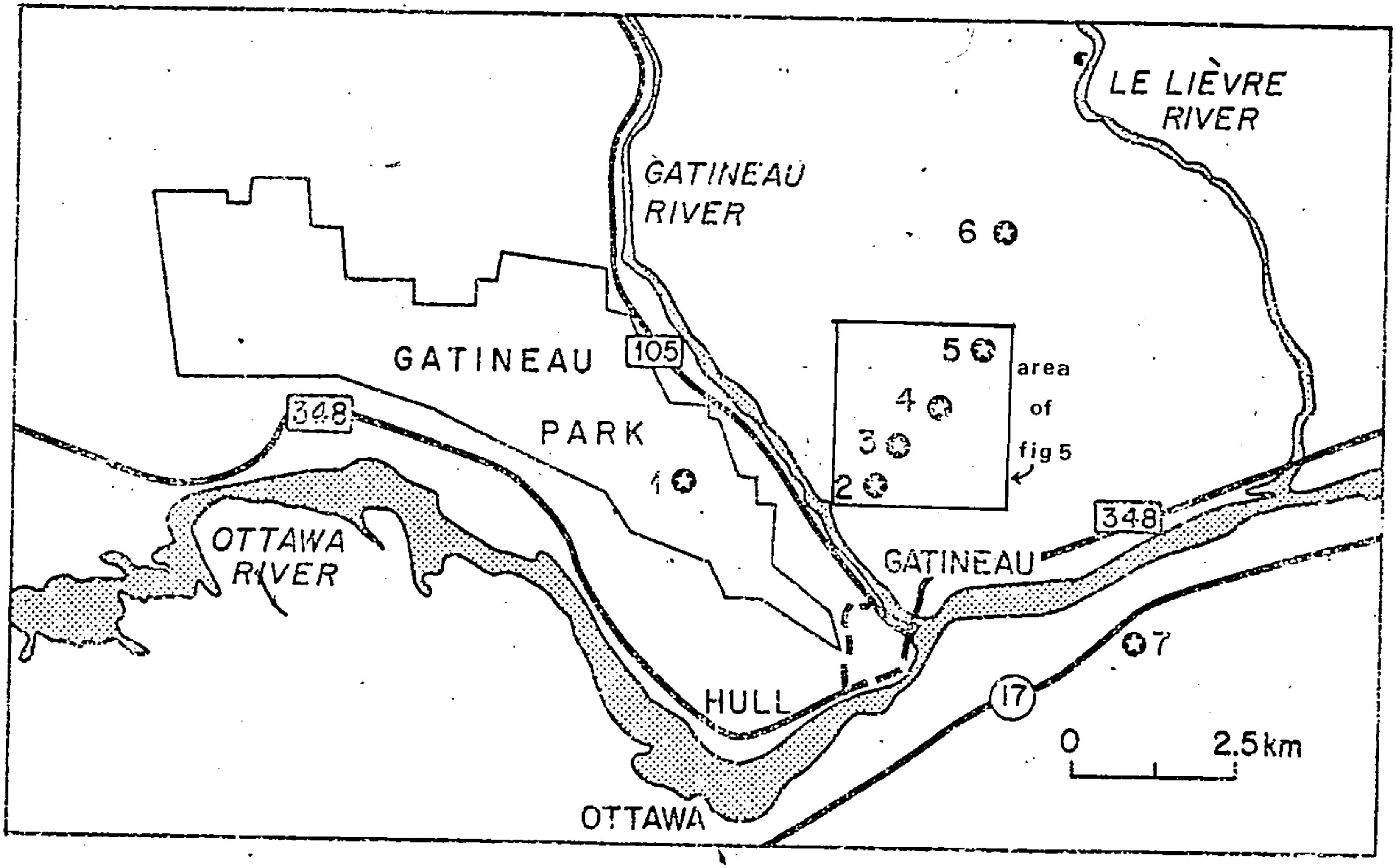

Figure 1. Map of Gatineau-Lievre area showing localities of alkalic rocks.
1.Meach Lake 2. Viau's Lot 3. Haycock Mine
4.Flynn Lot 5. Rainville Creek 6.Little Dam Lake
7.Francon Quarry

Township boundary divides the area in half (Fig. 2). The Haycock hematite-magnetite deposits and associated alkalic-magnesian rocks are included in an area of about 400 acres in lot 1, range XI of Hull Township and lot 28, range VI of Templeton Township. The area is easily accessible by car, and both municipal and forestry roads cross the entire region. The physiography is characterized by low relief with gently rolling hills and extensive intervening marshlands. This low relief also results in poor rock exposure, approximately 70 percent of the area being drift or swamp-covered.

1.3 Mining History

The Haycock Mine was worked for iron by Edward Haycock from 1872 to 1874. It was described by Cirkel (1909, pp. 61) as follows:

> "In April, 1873, extensive operations were started, which lasted, with few interruptions, until the fall of the following year. During this time a number of dwelling houses, offices, storehouses, residence for manager, stables, and powderhouse were built, and the property put in shape generally for work on an extensive scale. There were also built four charcoal kilns, a forge of four fires in which very good blooms were made, a crusher house, and all accessories for combined mining and smelting operations. A tramway, 3 feet gauge, 6 1/4 miles in length, was built from the

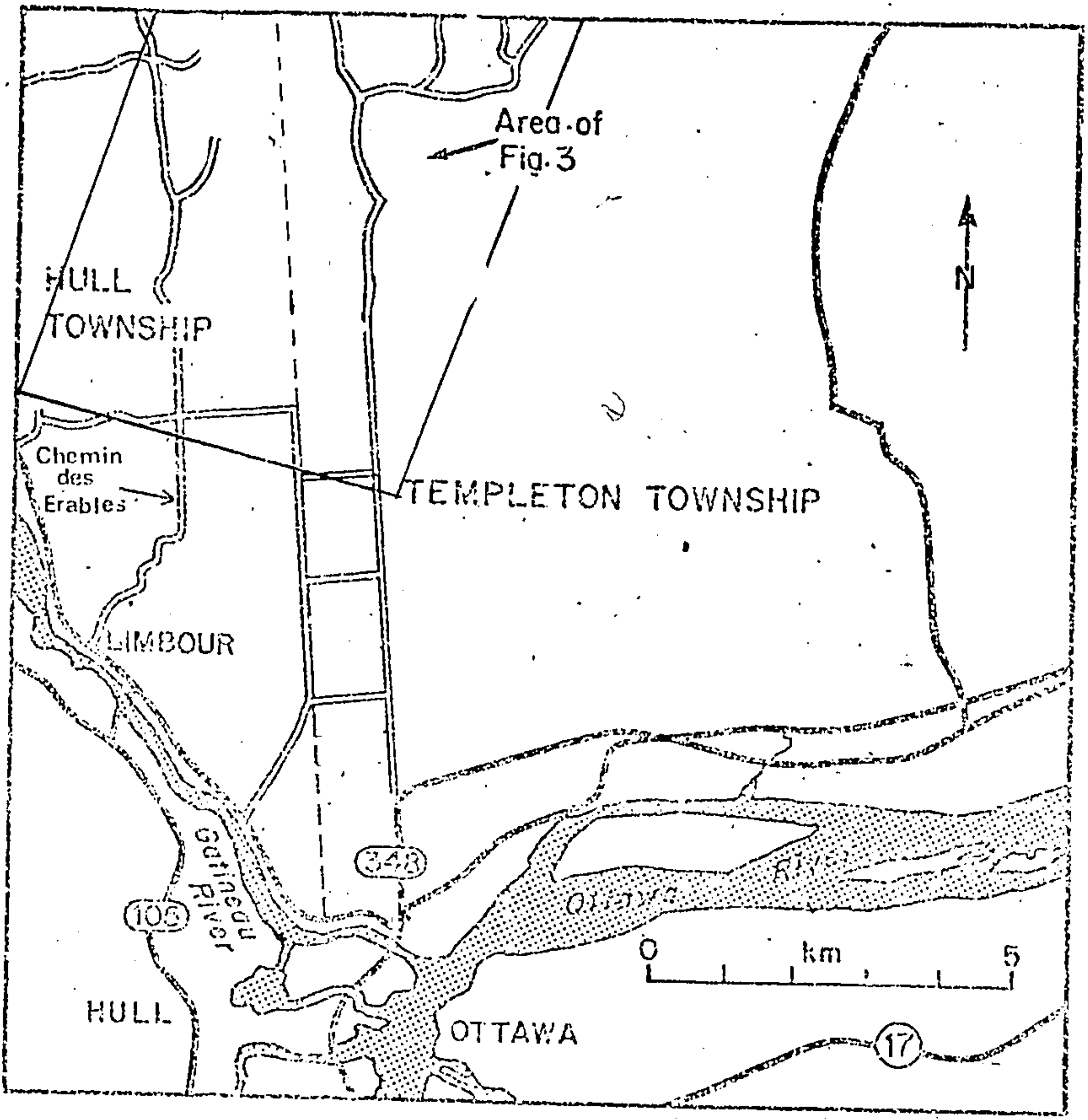

Figure 2 Location map of the area studied. Modified from N.T.S. map of the Ottawa-Gatineau District (1953). Township line follows Chemin des Erables in an approximately northerly direction.

> principal pits, through the property along the town line between Hull and Templeton, to the Gatineau River, where the connection was made with the Canadian Pacific Railway and all connecting railway and streamship lines at Ottawa and Montreal. In addition to the above, a steam sawmill of 20 horse-power was erected, with all facilities for cutting timber and logs. As to the results of these operations, which extended over several years, no authentic information can be obtained. It appears, however, that while the quality of the ore was excellent, the quantity necessary to keep the furnaces permanently in operation seems to have been lacking."

It should be noted that this was one of the earliest mines in central Canada and the mining industry contributed to the opening-up of the Ottawa Valley district.

1.4 Research Methods

Sample collecting and geological mapping were done in the fall of 1972 and spring and summer of 1973. In total 5 weeks were spent in the field, about 3.5 weeks mapping and collecting in the mine area and vicinity (area of Fig. 6), the remaining 1.5 weeks in a general geological reconnaissance (area of Fig. 3) by examining outcrops at or near roads and trails. Plotting was on black and white aerial photographs (1:12,000 scale). Figure 6 is from personal observation whereas the geology of Figure 3 is from Dr. Hogarth's unpublished manuscript map with generalizations and alterations after observations of the writer.

On the mine property, sampling was done by two techniques: by collecting block samples and by coring. From a large selection of block samples (2-3 kg) 40 were selected for detailed chemical and petrological study. Considerable care was taken to ensure representativity but in some instances, owing to extreme coarse grain and inhomogeneity, this proved impossible for a reasonably sized sample. Effects of this inhomogeneity will be apparent in analyses quoted in Section 5.

Polished and thin sections were cut from these block samples for detailed petrographic investigation. The remainder was crushed to 200 mesh for chemical analyses. About 100 cores (2.5 cm diameter, 15 cm in length) were drilled in the immediate area of the Haycock Mine with a portable gas driven drill. From these, 20 were selected for detailed examination and it was from these cores that the polished thin sections for electron microprobe analyses were cut. No cores were drilled outside the area of Fig. 6.

1.5 Acknowledgments

I wish to thank Dr. D.D. Hogarth for suggesting the project and for a comprehensive supervision. My thanks are also given to the following persons for comments and help on some aspects of the thesis: Dr. Philip Manning, Department of the Environment, Ottawa, for the use of optical spectroscopy equipment, Dr. M.G. Townsend, Mines Branch, Ottawa, for the use of Mossbauer equipment, Dr. D. Watkinson, Carleton University and Dr. G. Armbrust, Department of Geology, University of Ottawa, Ottawa, for helpful comments and discussion.

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CHAPTER 2

REGIONAL GEOLOGY

2.1 General Statement

Rocks of the Ottawa-Hull area were formed both in Precambrian and Phanerozoic time. The St. Lawrence Lowlands are covered by Paleozoic and Quaternary sedimentary rocks. The flanking hilly country is mainly underlain by Precambrian regional metamorphic rocks with grades up to granulite facies. The latest metamorphic episode was the Grenvillian Orogeny which gives K-Ar ages of 900 to 1100 m.y. (Baird, 1972).

2.2 Previous Geological Work

The first geological description of the Haycock Mine area was by Logan (1866, pp. 20-22). This was followed by reconnaissance mapping by Vennor (1878) and Ells (1901a,b). Historical and descriptive information was presented for most iron deposits in the Gatineau area by Cirkel (1909, pp. 60-72). The area was mapped on a scale of 1/63,360 by M.E. Wilson (1920) and described in a preliminary report (Wilson, 1916). The economic mineral deposits of the same area, were described by A. Ledoux (1916). General geology of the region northwest and west of the thesis area is found in the reports of the Wakefield area by Beland (1954, 1955). A guide book by Hogarth

(1962) describes the Haycock Mine and other localities. The nearby area, Gatineau Park has been described and mapped by Hogarth (1966, 1970). A B.Sc. thesis by Cockburn (1966) describes the ore deposits of the Haycock Mine. A good resume of the Ottawa-Hull general geology and a summary of the Haycock Mine geology can be found in the 24th International Geological Congress Guide Book to excursions B-23 to B-27 edited by D.M. Baird (1972).

2.3 Rock Descriptions

Rocks are classified genetically as metasedimentary and meta-igneous units.

2.3.1 Meta-sedimentary Unit

This unit consists of marble, paragneiss and quartzite. The marble consists of coarse-grained calcite and varies from a relatively pure marble (southwest corner Fig. 3) containing dolomite, phlogopite and apatite to a very impure marble (northeast corner Fig. 3) composed of calcite (45%), apatite (20%) and phlogopite (35%). This rock has undergone strong serpentinization. Xenoliths consist of quartzite and paragneiss. No regular alignment of these blocks was found. The quartzite is massive and coarse grained, containing quartz, biotite, iron oxides, hornblende and feldspar. Paragneiss is associated with, and gradational into,

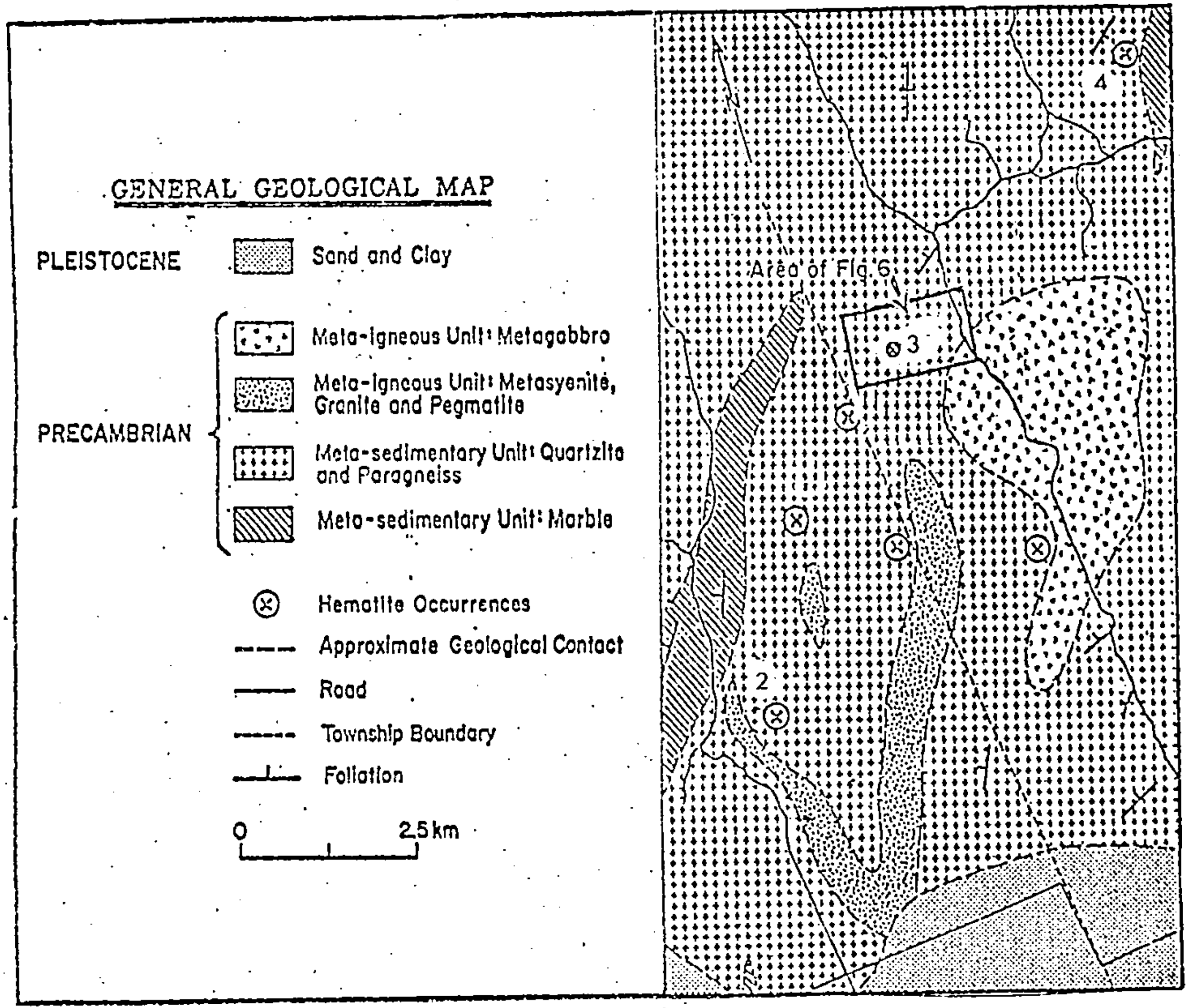

Figure 3 General geological map of the studied area.

(combined compilation with D.D.Hogarth)

quartzite as layers and lenticular masses. No extensive area of outcrops was found. The gneiss varies greatly in composition but generally is composed of quartz, biotite and microcline locally with considerable almandine and/or hypersthene (rarely sillimanite).

2.3.2 The Meta-igneous Unit

This unit is composed of metagabbro, metasyenite granite, pegmatite, and a carbonate-sulfate rock. Throughout the area dikes and irregular masses of pegmatite are found. They consist of microcline-albite or microcline-oligoclase and varying amounts of quartz and ferromagnesian minerals. Their appearance is fresher than other rocks. They were probably formed at a late stage of magmatism. Biotite gneiss, containing varying amounts of quartz, is the wall rock of the Haycock iron deposits. It perhaps belongs with this unit and will be discussed in later sections of the thesis. A small (2 meter-diameter) isolated rock, crops out at location 15 (Fig. 6, figure caption). The small size of this outcrop and its unexposed field relationships with surrounding rocks preclude any definite conclusion on its origin. The rock is inhomogeneous and consists of calcite (45%), dolomite (20%) and barite (35%). Large crystals of magnetite are sparsely distributed through the rock. This mineralogy is not inconsistent with either igneous (carbonatite) or hydrothermal origins.

CHAPTER 3

FENITES AND ALKALIC ROCKS

3.1 Definition

The term fenite will be employed throughout the thesis and should therefore be defined at the outset. Originally "fenite" was applied to the contact metamorphic aureole of the Fen eruptive rock, Norway (Brogger, 1921). It was defined as: leucometasomatite of altered granite developed through the action of solutions derived from an ijolite-melteigite magma and containing up to 25 percent aegirine-augite and a minimum of 52 percent of SiO_2. It was later found around many carbonatite complexes. The usage of the word has broadened and it was defined by Gary et al. (1973) as a "quartz-feldspathic rock which has been altered by alkali-metasomatism at the contact of a carbonatite intrusive complex".

In the present study no alkalic intrusions or carbonatites were found, although these may not crop out on the surface. Fenite will therefore be used for a rock with similar mineralogy to the fenite of Fen (i.e. containing such minerals as aegirine, iron oxides and alkali amphiboles) resulting from the alkali action on the country rocks. Although the word fenite is used, it is clear that one has to be careful, and that alkaline iron-rich rock might be more appropriate.

Since the recognition of the economic potential of carbonatites and alkalic rocks (for example those from Oka, Quebec and the Kola Peninsula, USSR) the study of these rocks has been intensified. The best references covering fenites are the Alno Memoir by Von Eckermann (1948), the two basic textbooks on carbonatites by Heinrich (1966) and Tuttle and Gittins (1966), the symposium on alkalic rocks, G. Perrault editor (1970) and the textbook on alkalic rocks by Sørensen (1974).

3.2 Regional Setting

The tectonic setting of the Ottawa-Hull area is the Ottawa graben, a down-dropped block of basement rock mostly covered with Paleozoic sediments (Fig. 4). This graben is considered to be an arm of the St. Lawrence rift system (Kumarapeli, 1970). The correlation between this rift system, or its extension arms, with alkaline activity in time and space, was established by Kumarapeli and Saull (1966), Kumarapeli (1970) and Doig (1970). They proposed a Precambrian origin of the rift system with later episodic alkaline igneous activity at around 120 m.y. (Monteregian intrusion), at 350-450 m.y. (Rigaud stock) and 500-600 m.y. (Buckingham intrusive complex). Other alkaline rocks are found, in northeastern Ontario, representing episodes at 1000-1100 m.y. and 1650-1750 m.y. (Tuttle and Gittins, 1966). Some are thought to be related to the Kapuskasing gravity high, and correspond closely to the Grenvillian and Hudsonian events.

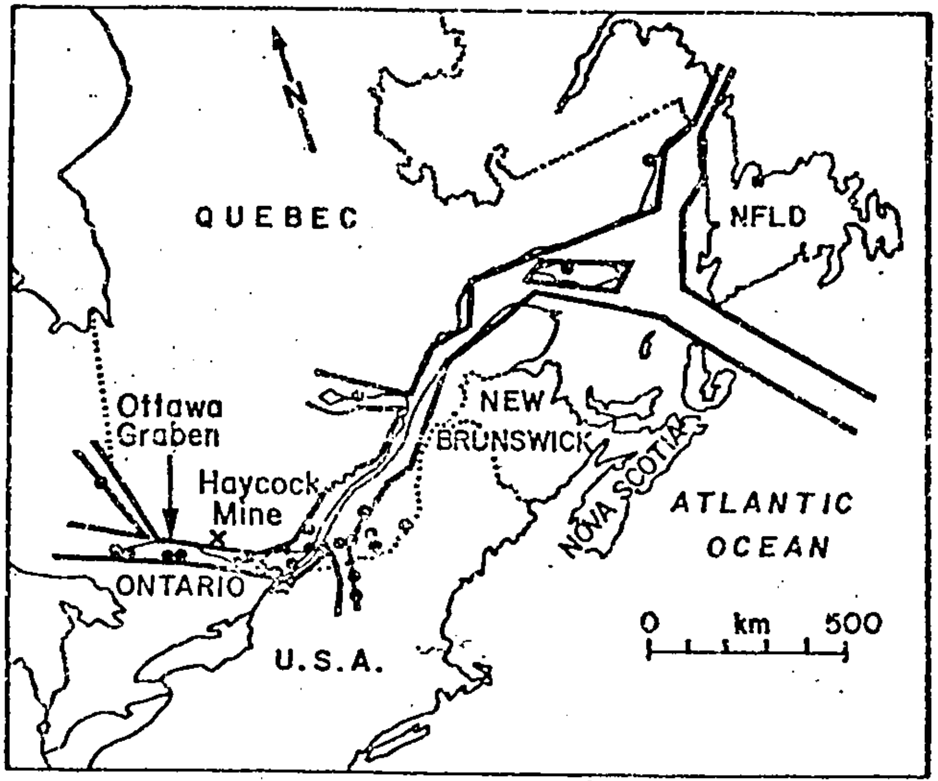

Figure 4. Distribution of dated alkaline igneous rocks of Phanerozoic age in Eastern Canada. (shown as full dot). The boundaries of the St. Lawrence rift system are shown in heavy lines from Kumarapeli and Saull (1966). They concluded that the origin of the rift system may have been in Precambrian time.

The boundaries of the Ottawa Graben in the study area are poorly defined due to lack of good outcrops. Geographically, the Haycock Mine appears to lie close to the north boundary of the graben and this suggests a possible genetic relation between the two, though lacking further evidence, this relationship is tenuous. The Haycock occurrences, however, give Precambrian ages (next section) and this would require the fault system of the graben to be in existence over a very long period of time.

3.3 Alkalic Rocks in Hull and Templeton Townships

Three types of alkalic rocks are known in the Ottawa-Hull area (Fig. 1).

1) Aplites and carbonatites near Meach Lake, northeast of Hull, Quebec (Béland, 1951; Hogarth, 1966; and Baird, 1972).
2) Carbonatite dykes in the Francon Quarry, Orleans, Ontario (Baird, 1972).
3) Fenite and associated rocks at Haycock Mine, Little Dam Lake, Rainville Creek, and Darby's, Viau's and Flynn's Lots (Cirkel, 1909; Cockburn, 1966, Baird, 1972, Erdmer, 1977).

The Meach Lake carbonatite complex is associated with the late stage of the Wakefield Batholith and consists of dolomite-calcite bodies associated with richterite and magnesioriebeckite, and as minor constituents, apatite, phlogopite, strontianite, barite, fluorite, betafite and other minerals. Two ages (K-Ar) were determined on phlogopite (D.D. Hogarth, 1966):

a) Brown phlogopite selvedge from a dolomite-calcite dyke (930 ± 25 m.y.).

b) Green phlogopite selvedge from a calcite dyke (910 ± 25 m.y.).

The Francon Quarry dolomitic carbonatite dykes cut Middle Ordovician limestone and may be contemporaneous with Monteregian intrusives to the east. The carbonatite dykes occur in a regionally developed shatter zone which cuts the Ottawa Formation. Besides a dolomitic-calcite matrix the dykes contain scattered phenocrysts of phlogopite and apatite. They are parallel to a regional set of normal faults and trend 90°/85° S. The matrix is dolomitic and the rock is rich in rare earths (La, Ce) and Nb, Mo, Sr (Baird, 1972).

Fenites near the Hull-Templeton township line have a different mineralogy. All contain hematite (either as red hematite or specularite), aegirine and Na-amphibole. All have high titanium content; rutile is recorded at the Haycock Mine, Rainville Creek, and Little Dam Lake. Barite is seen at the Haycock Mine, Rainville Creek and Little Dam Lake. At the Haycock Mine, minerals are arranged in zones around iron-oxide lenses. Proceeding outward, the zones are characterized by hematite-magnetite (core), aegirine-eckermannite-phlogopite (inner), and aegirine-phlogopite (outer). They will be described in detail in Chapter 5.

Two K/Ar ages on brown phlogopite from the Haycock Mine give a mean age of 921 m.y. They are:

1) Brown phlogopite from fenite dump (980 ± 52 m.y.) (M. Shafiquillah, Carleton University, Ottawa for D.D. Hogarth, 1971).
2) Brown phlogopite from fenite from the Haycock Mine Adit: (862 ± 31 m.y.) (Wanless _et al_., 1974, pp. 72-88

3.4 Spatial Relationships of Occurrence

Two spatial relationships are apparent. First is the regional north-northeast alignment of iron oxide occurrences (Fig. 1). This north-northeast trend correlates with the magnetic high (>2800 gammas; Fig. 5) which corresponds to an area underlain by biotite gneiss (Fig. 3). Secondly the flanking magnetic lows (<2800 gammas) correspond to typical metasedimentary rocks. This alignment suggests a stratigraphic control.

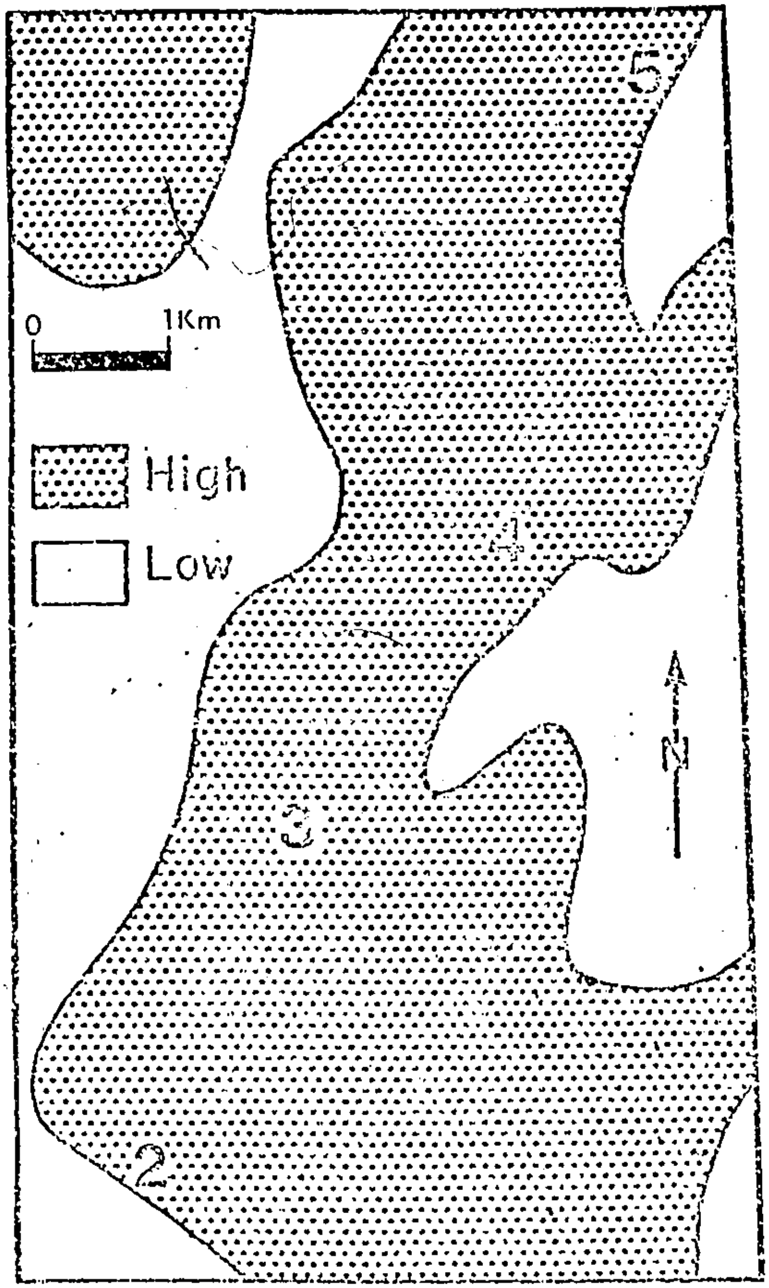

Figure 5 Aeromagnetic map of the study area (Map 196-C, G.S.C.). Numbers in this figure are defined in Fig. 1. The high area signifies a total intensity greater than 2800 gammas and the low, less than 2800 gammas. Flight altitude 150 metres above ground level. Scale is 1:63,360.

CHAPTER 4

MINERALS

4.1 Introduction

This chapter will be devoted to the description of minerals found in the ore zone, fenites and in various surrounding rocks. The minerals found are divided in four groups: silicates, carbonates, oxides and others (Table 1).

TABLE 1

LIST OF MINERALS IN IRON ALKALIC DEPOSITS, HAYCOCK MINE AREA

Silicates:	Aegirine	Feldspars	Quartz
	Almandine*	Grunerite*	Scolecite
	Augite*	Hornblende*	Sericite
	Biotite*	Hypersthene*	Sillimanite*
	Chlorite*	Magnesioriebeckite	
	Eckermannite	Phlogopite	
Carbonates:	Calcite	Dolomite	
Oxides:	Hematite	Maghemite	Pseudobrookite
	Ilmenite	Magnetite	Rutile
Others:	Apatite	Fluorite	Pyrrhotite
	Barite	Pyrite	

*Minerals marked with an asterisk (*) have been found in the surrounding rock only.

4.4.2 Silicates

4.4.2.1 Aegirine

After phlogopite, aegirine is the most abundant gangue mineral. It is found in the fenite zones associated primarily with phlogopite, eckermannite, hematite and apatite in the inner and with phlogopite in the outer zone. It is also seen with calcite and barite in late veins. When associated with phlogopite, eckermannite and hematite, it occurs in two crystal habits: first as short, euhedral green crystals, second as small, bent light-green fibres. When associated with calcite and barite it occurs as short to long, commonly radiating fibres. Aegirine from different locations (Fig. 6) has been analyzed and chemical data are presented in Table 2. Very little variation in chemical composition from one zone to another is seen.

The name aegirine, as defined by Deer _et_ _al_. (1963, pp. 280), will be used to describe this species. Mossbauer and optical spectroscopy runs were made on aegirine crystals, results are presented in Appendix I. Diffractometer and camera X-ray studies were made and data are presented in Appendix II.

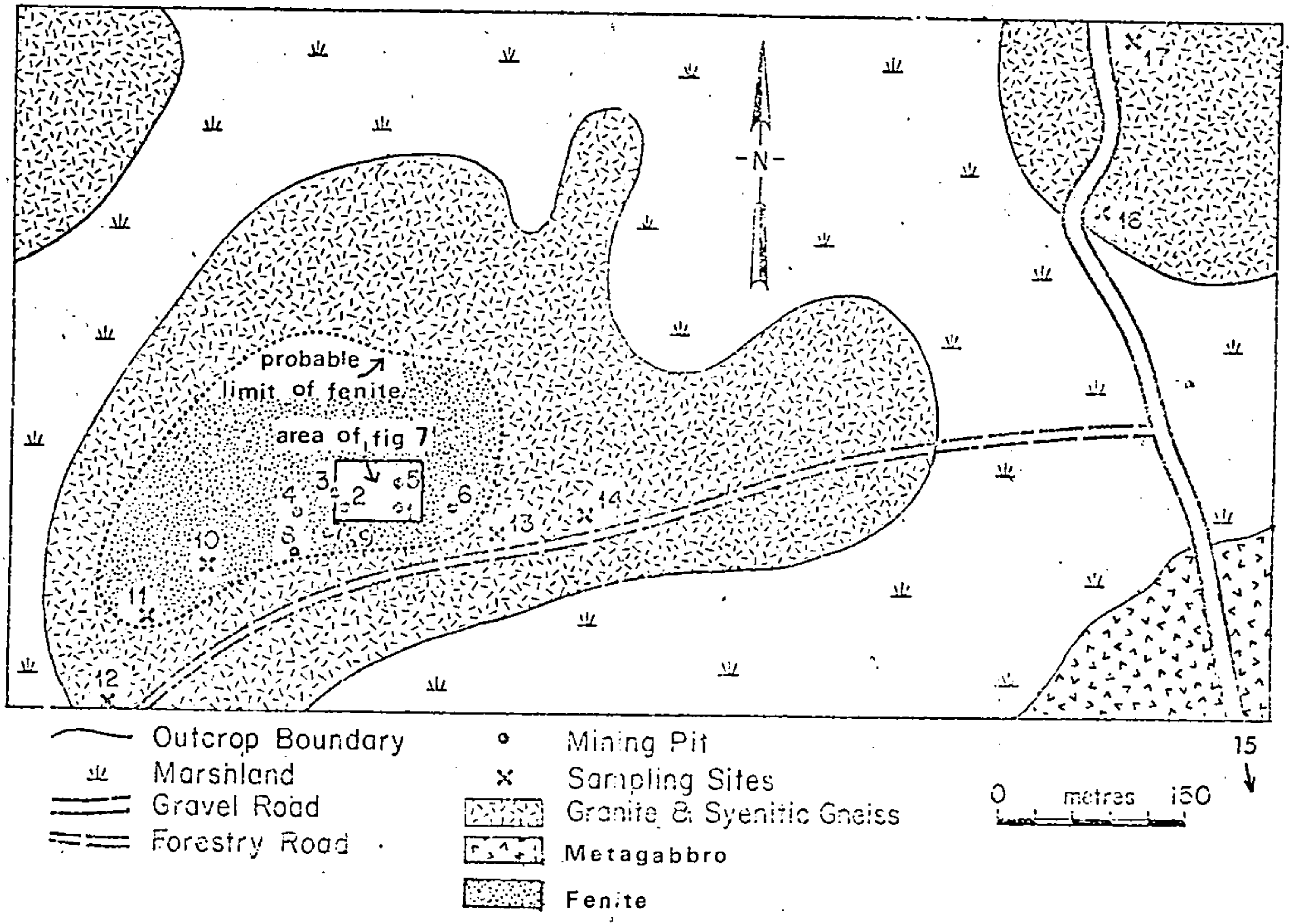

Figure 6 Map of Haycock mine and sampling sites. These sites are described in the Appendix.

TABLE 2

MICROPROBE ANALYSES OF AEGIRINE

FROM DIFFERENT AREAS OF FENITE ZONES

Location	01	02	07	09
SiO_2	52.67	54.23	53.05	52.57
TiO_2	0.18	0.44	0.80	0.05
Al_2O_3	2.91	1.46	1.74	2.37
Fe_2O_3**	32.44	29.89	31.17	31.92
MgO	0.25	0.35	0.68	0.24
CaO	0.34	0.22	0.39	0.19
Na_2O	13.11	13.78	14.68	14.17
K_2O	0.37	0.11	0.29	0.01
TOTAL	102.27	100.48	102.80	101.52

* Analyst Tariq Ahmegdali. Localities shown in Fig. 6. All inner zone samples.

**Total Fe as Fe_2O_3.

NUMBERS OF CATIONS BASED ON 6 OXYGENS

	01		02		07		09	
Si	1.962	2.00	2.038	2.04	1.972	2.00	1.974	2.00
Al^{+4}	0.038		0.000		0.028		0.026	
Al^{+6}	0.090	1.02	0.065	0.94	0.048	0.98	0.079	0.99
Ti	0.005		0.012		0.022		0.001	
Fe	0.909		0.845		0.872		0.902	
Mg	0.014		0.020		0.038		0.013	
Ca	0.014		0.009		0.016		0.008	
Na	0.947	0.98	1.004	1.2	1.058	1.09	1.032	1.04
K	0.018		0.005		0.014		0.000	

MOLECULAR PER UNIT

	01	02	07	09
Acmite	90.91	93.99	93.46	90.97
Jadeite	4.20	3.86	2.83	8.56
Rem.*	4.88	2.16	3.70	1.38

*Includes $CaTiAl_2O_6$, $Mg_2Si_2O_6$ end members.

Calculations according to the PYROX program, University of Oslo.

4.4.2.2 Almandine and Sillimanite

These minerals are found in the sillimanite-garnet-biotite gneiss only. Sillimanite is sparsely distributed in the gneiss, occurring as prisms within quartz and microcline. Garnet is rare near the Haycock mine but is common in the northeast corner of the map area associated with quartz, biotite, sillimanite and microcline. Garnet (almandine) is found as rounded crystals. X-ray data for sillimante and the garnet, identified as almandine are presented in Appendix II.

4.4.2.3 Augite, Biotite, Chlorite, Hypersthene and Grunerite

These ferromagnesian minerals are constituents of the meta-igneous unit but chlorite and biotite are also seen in the metasedimentary unit. In the marble, a minor amount of chlorite and phlogopite can be detected. Chlorite and biotite are common near the mine area. In syenite near the mine, chlorite appears to decrease with distance from the mine but any conclusions are speculative owing to the scarcity of the outcrops. Grunerite is seen in the northeast edge of the mine but rarely outside the mine area. Augite and Hypersthene are minor constituents.

4.4.2.4 Eckermannite

Eckermannite occurs exclusively in the fenite zones where it is always associated with phlogopite and aegirine. In hand specimens it is easily recognized by its fibrous appearance, its light blue color and its characteristic mineral assemblages: aegirine (green) and phlogopite (brown to black). In thin section, its pleochoism is from purple to blue, anomalous interference colors (from Berlin blue to brown, with a sharp change) which are easily recognized.1 It is difficult to determine optical properties owing to its fibrous form. Chemical analyses from different areas (Fig. 6) within the inner zone are presented in Table 3.

As seen from these analyses there are no appreciable changes within the zone itself. The main variation in amphiboles appears to be in the different species found at and near the Haycock mine (eckermannite) and that found in the surrounding area (magnesioriebeckite). This conclusion, is however, based on a single analysis of magnesioriebectite. X-ray diffraction studies were precluded due to the difficulty in purifying the mineral. Mossbauer spectra runs were made on eckermannite and the pertinent data are tabulated in Appendix I.

TABLE 3

MICROPROBE ANALYSES OF ECKERMANNITE*

Locations	01	09
SiO_2	57.08	56.04
TiO_2	0.10	0.12
Al_2O_3	0.44	0.45
Fe_2O_3**	7.76	8.13
FeO	3.28	3.46
MgO	16.75	16.30
CaO	0.52	0.34
Na_2O	8.71	9.06
K_2O	2.41	2.38
TOTAL	97.05	96.28

NUMBERS OF CATIONS BASED ON 46 CHARGES

	01		09	
Si	8.099	8.10	8.121	8.12
Al^{IV}	0.000		0.000	
Al^{VI}	0.074	4.85	0.077	4.97
Ti	0.011		0.013	
Fe	0.829		0.985	
Fe	0.389		0.377	
Mg	3.543		3.521	
Ca	0.079	2.91	0.053	3.04
Na	2.396		2.545	
K	0.436		0.440	

* Analyst Tariq Ahmegdali

** Analysed total Fe was resolved in FeO and Fe_2O_3 from Mossbauer data. Sample locations shown on Fig. 6.

4.4.2.5 Feldspar and Sericite

Alkali-feldspars (microcline) from different areas of the inner and outer fenite zones (Fig. 6) were analysed (Table 4) and confirmed by X-ray diffraction (Appendix II). Little chemical variation was detected. It must be noted that the increase in fenitization is characterized by an increase in sericitization of the feldspar and by the formation of a new plagioclase, in the form of fresh subhedral crystals of composition An_{10} (optical determination). The formation of this new feldspar implies that calcium needs to be brought in. The origin of the calcium addition is unknown.

4.4.2.6 Magnesioriebeckite

Magnesioriebeckite was identified in the second type fenite, i.e. that found outside the immediate area of the Haycock Mine, filling fractures and coating joints and slickensides. It is associated with minor hematite and calcite. The mineral is present as very fine blue needles and was never found in any other crystal habit. In thin sections it is recognized by its strong pleochroism (blue to green) and anomalous deep blue to brown interference colors. X-ray data and chemical analyses for magnesioriebeckite are presented respectively in Appendix II and Table 5. The occurrence of

TABLE 4

MICROPROBE ANALYSES OF MICROCLINE*

FROM DIFFERENT FENITE ZONES

Location	1	2	7	9
ZONE	INNER	INNER	OUTER	OUTER
SiO_2	64.28	64.26	64.60	62.38
Al_2O_3	18.25	18.77	17.91	18.52
FeO**	0.25	0.19	0.35	0.06
MgO	0.02	0.00	0.01	0.00
CaO	0.04	0.09	0.01	0.07
Na_2O	0.50	1.04	0.40	1.25
K_2O	16.42	14.68	16.23	15.50
TOTAL	99.76	99.23	99.51	97.78

* Analyst Tariq Ahmegdali. Location from Fig. 6.

** Total Fe as FeO

NUMBERS OF CATIONS BASED ON 8 OXYGENS

Si	2.995	4.00	3.082	4.14	2.995	4.00	2.940	3.96
Al	1.002		1.058		1.005		1.019	
Fe	0.001	1.02	0.008	1.00	0.014	1.04	0.002	1.04
Ca	0.002		0.005		0.001		0.003	
Na	0.045		0.096		0.037		0.113	
K	0.976		0.896		0.986		0.924	

TABLE 5

ATOMIC ABSORPTION ANALYSES OF MAGNESIORIEBECKITE*

SiO_2	55.15
Al_2O_3	1.14
Fe_2O_3	13.60
FeO	8.24
MgO	10.04
CaO	2.23
MnO	0.14
Na_2O	5.43
K_2O	0.28
TOTAL	96.25

NUMBER OF CATIONS PER 46 NEGATIVE CHARGES

Si	8.055	8.06
Al^{IV}	0.000	
Al^{VI}	0.196	4.90
Fe^{+III}	1.495	
Fe^{+II}	1.006	
Mn	0.017	
Mg	2.186	
Ca	0.349	1.94
Na	1.538	
K	0.052	

*Ferric and Ferrous iron resolved by method of Jen (1973). Location 17 in Fig. 6.

magnesioriebeckite is of prime importance since it has been recognized in many areas of tectonic activity like the Great Glen Fault in Scotland where crocidolite fills joints and shear zones and coats slickensides (Deans, 1970).

4.4.2.7 Phlogopite

Phlogopite is the most abundant gangue mineral. It is a major component of veinlets, lenses and pods in both core and fenite zones. In the core zone it is associated with ore minerals, in the inner zone it is associated with aegirine and eckermannite. In the outer zone it is found with aegirine. In addition it is invariably present in small amounts in late calcite veins. When in contact with the ore minerals it tends to form large euhedral crystals; when associated with fenite minerals, it tends to form small crystals lacking side terminations. Chemical variation among analyses from the different zones is small (Table 6).

4.4.2.8 Quartz

Quartz is a minor constituent (less than 1% per volume) in the ore zone. It also occurs as late veins cutting the ore and fenite.

4.4.2.9 Scolecite

Scolecite (zeolite mineral) was recorded by Baird (1972) but was not identified in the samples collected.

TABLE 6

MICROPROBE ANALYSES* OF PHLOGOPITE FROM DIFFERENT AREAS OF FENITE ZONES

Locations	1	7	9
ZONE	ORE	INNER	INNER
SiO_2	41.99	45.26	45.86
TiO_2	0.27	0.16	0.12
Al_2O_3	11.63	9.27	9.97
FeO**	6.49	0.96	3.11
MgO	22.61	24.17	24.60
CaO	0.00	0.04	0.00
Na_2O	1.06	0.65	0.43
K_2O	8.80	11.52	10.48
TOTAL	92.85	92.03	94.49

* Analyst: Tariq Ahmegdali, locations from Fig. 6.

** Total Fe as FeO

NUMBERS OF CATIONS BASED ON 22 OXYGENS

Si	6.127	8.00	6.548	8.00	6.471	8.00
Al^{IV}	1.873		1.452		1.529	
Al^{VI}	0.127	5.88	0.129	5.48	0.129	5.69
Ti	0.029		0.017		0.013	
Fe	0.792		0.116		0.368	
Mg	4.919		5.217		5.177	
Na	0.150	2.15	0.108	2.24	0.118	1.19
K	2.000		2.127		1.873	
Ca	–		0.006		–	

4.3 Carbonates

4.3.1 Calcite

Calcite is commonly associated with barite and fills cavities in hematite and magnetite. It is also found as late phase veinlets cutting the ore and fenite zones. Outside the complex, it is a major constituent of marble associated with minor dolomite, phlogopite and apatite. As described earlier under carbonate rocks, calcite occurs with barite dolomite and magnetite in an unusual rock in one location only. Chemical analyses of calcite from different areas are presented in Table 7. These analyses were made from carbonates in different veinlets cutting the fenite (Location in Fig. 6).

Calcite associated with the ore zone is white to pinkish and anhedral. The calcite from the carbonate rock is red and in large crystals when in contact with the surrounding gneiss, and small anhedral grains with increasing dolomite and barite content near the central part of the outcrop. Calcite from the core zone was tested by X-ray powder diffraction and data are presented in Appendix III.

TABLE 7

PARTIAL MICROPROBE ANALYSES OF CALCITE FROM DIFFERENT AREAS OF FENITE ZONES*

Location	1	2	3	4	5
FeO**	0.06	0.15	0.16	0.10	0.14
BaO	0.13	0.17	0.02	0.01	0.05
MgO	0.11	0.13	0.20	0.08	0.37
SrO	1.75	0.09	0.00	0.01	0.05

* Analyst T. Ahmegdali

Sample locations in Figure 6.

**Total Fe as FeO.

4.3.2 Dolomite

Dolomite is a constituent of two rock units. It is a major constituent of marble with calcite; phlogopite and apatite. It is found in a carbonate rock unit associated with calcite and barite in the central part of the outcrop as large euhedral crystals.

4.4 Oxides

4.4.1 Hematite

Hematite is the predominant ore mineral found in the mine area. There are two types of hematite: the first type, large euhedral crystals with a rutile intergrowth, the second type as anhedral martite grains, with magnetite and maghemite. Chemical analyses are presented in table 8 but will be discussed in the Chapter on fenitization. The two associations, hematite-rutile, hematite-magnetite are from different parts of the same polished section (G.H.C. 28).

4.4.2 Magnetite

Magnetite crystals are large euhedral and, even, if brecciated, the small fragments retain their original orientation which suggest insignificant bending. Chemical analyses are given in Table 8.

4.4.3 Maghemite

Maghemite in hematite was identified during a Curie point analysis. The sample was from location 1.

4.4.4 Rutile

Epitaxial grains of titania were established by microprobe analyses (Table 8) and probably represent rutile. The grains are microlamellae oriented in a single plane in hematite possibly with an orientation $(010)\ [101]$ rutile $\parallel$ $(0001)\ [10\bar{1}0]$ hematite (Palache

TABLE 8

MICROPROBE ANALYSES OF OXIDE MINERALS*

Coexisting Pair	Hm-Ru-1	Hm-Ru-2	Mgt-Hm-1	Mgt-Hm-2	Hm-Mgt-1	Hm-Mgt-2	Ru-Hm-1	Ru-Hm-2
Phase	Hm**	Hm	Mgt***	Mgt	Hm	Hm	Ru	Ru
FeO	6.13	9.76	39.35	38.63	8.92	7.11	0.57	0.65
Fe_2O_3	87.00	78.81	50.84	51.64	81.67	85.49	-	-
TiO_2	6.82	10.85	9.16	8.56	9.92	7.91	100.18	100.64
TOTAL	99.96	99.42	99.35	98.83	99.01	100.51	101.18	101.29

* All three phases coexisted in this polished section (GHC 28)

** Charge balance assumed to be maintained by the coupled substitution $2Fe^{3+}=Fe^{2+}+Ti^{4+}$

*** Charge balance assumed $Fe^{2+} + 2Fe^{3+} = Ti^{4+} + 2Fe^{2+}$

Hm = Hematite

Ru = Rutile

Mgt = Magnetite

Location of specimen, 1 in Fig. 6.

Analyst Ms. P. Morton, Carleton University *et al*. 1944, p. 556). The significance of this mineral is described in Chapter 5.

4.4.5 Pseudobrookite(?)

Pseudobrookite grows epitaxially within hematite. It was identified optically as lamellae oriented in three directions. Pseudobrookite was chosen because of its association with rutile and hematite (Haggerty and Lindsley, 1970). The proportion of pseudobrookite to rutile lamellae in hematite cannot be determined since many of the intergrowths apparently are submicroscopic. Pseudobrookite identification was done optically and was chosen over a possible ilmenite mainly because of its association with rutile and hematite.

4.4.6 Ilmenite

Ilmenite intergrowth were identified optically along octahedral planes of magnetite, especially in areas of strong martitisation. Ilmenite intergrowths extend into the martite.

4.5 Other Minerals

4.5.1 Apatite

Apatite is the third most abundant gangue mineral. It is observed with hematite, magnetite, and calcite as subhedral grains. Its distribution is sporadic but when calcite is present, the apatite content always increases. This effect was also reported by Cockburn (1966, p. 33).

4.5.2 Barite

Barite is associated with calcite. First filling cavities in hematite and magnetite crystals and second as late phase veinlets with calcite. It occurs also with dolomite and calcite in carbonate rocks. Barite is easily recognized by its white or pink color, its high density and its association with calcite. X-ray data for barite are presented in Appendix II.

CHAPTER 5

FENITIZATION AT THE HAYCOCK MINE

5.1 Introduction

Two types of fenite (alkaline iron rich rock) are recognized. The first is spatially related to the central hematite-magnetite deposit as a replacement envelope of the surrounding biotite gneiss. The replacement envelope is characterized by aegirine, eckermannite and phlogopite. The second type is found principally in the meta-igneous unit, as mineral (magnesioriebeckite, hematite, calcite) infillings of fractures, joints and coatings on slickensides.

Rocks derived by the first process resemble fenites associated with carbonatites (Fen, Alno, Oka). The second type is similar to fenitization (or metasomatism) near the Great Glen Fault (Deans et al., 1971) where crocidolite, aegirine and hematite occur on joints and slickenside.

5.2 Fenite Associated with the Main Deposit of Iron Ore

Based on characteristic mineral associations, rocks of the Haycock alkalic-iron mineralized area were divided into three zones; the core, the inner and outer fenites zones (Fig. 7). In the core zone, the hematite-magnetite content of the rock exceeds 30 percent by volume. The inner fenite

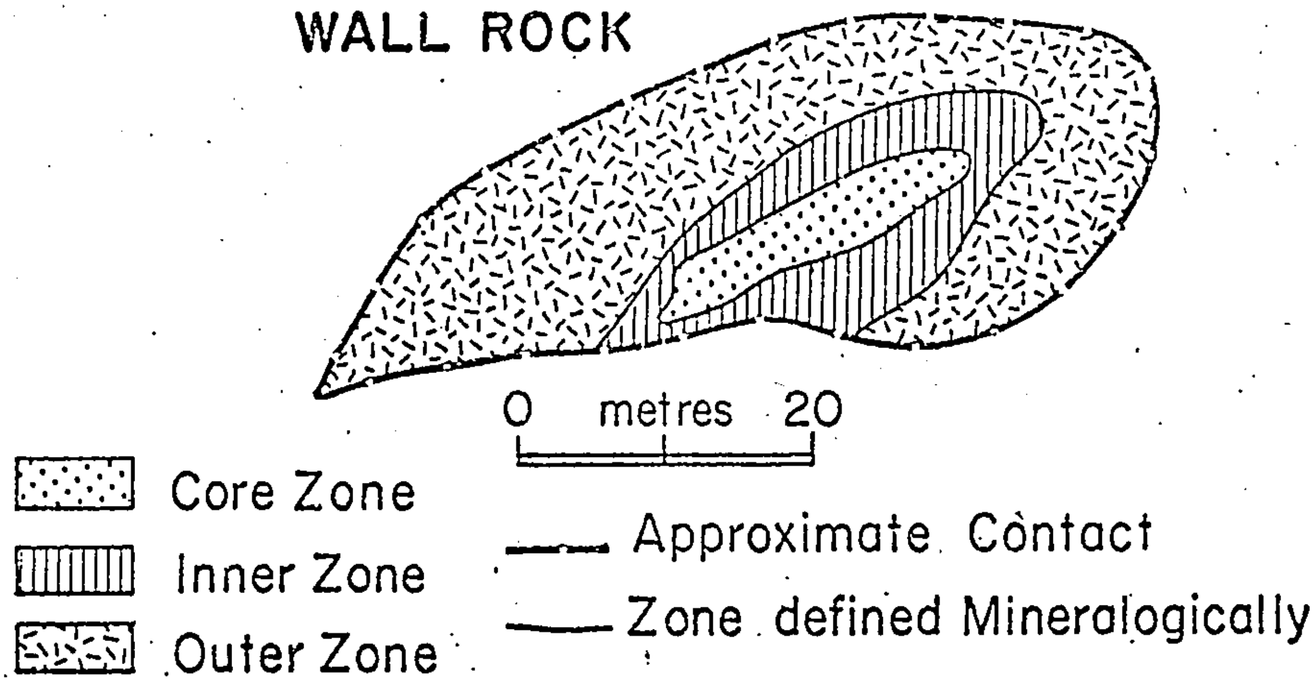

Figure 7. Schematic diagram of fenite zones. Based on localities 1 to 5 in fig. 6. A total of 40 samples (cores) were used to defined these zones

zone is based on the association of aegirine, eckermannite and phlogopite. The outer fenite zone is defined by the assemblage phlogopite and aegirine. The phlogopite content is normally greater than that of aegirine. Differences in modal and chemical analyses (Table 9) can be explained by the non-representativity of the bulk samples used for chemical analyses and even less in the case of thin sections. The metallic minerals were very coarse grained and irregularly distributed and therefore extremely difficult to sample.

To minimize this uneven distribution thin and polished section data were statistically weighted by a factor representing the proportion of opaque/silicate which was estimated to be 80/20.

Biotite gneiss is not considered a fenite although minor effects of fenitization may be locally present. Chlorite appears to decrease away from the fenite zones, although this pattern cannot definitely be linked with the fenitization process due to poor outcrop. The maximum chlorite content was seen to be 15 modal percent.

5.2.1 Outer Zone

Stable association: phlogopite-aegirine

This zone is comparatively large (Fig. 7) and is defined by the presence of phlogopite and aegirine or, more appropriately, the absence of eckermannite. The rock is composed of phlogopite, aegirine, cloudy feldspar (extensive sericitization), and a characteristically low hematite content. At the contact with late stage veins,phlogopite is always more abundant than aegirine.Chemical and modal analyses of this zone are presented in Table 11(which can be compared with country rock analyses,Table 10).

5.2.2 Inner Zone

Stable association: aegirine-phlogopite-eckermannite

The inner zone is characterized by the aegirine-phlogopite-eckermannite assemblage (Fig.7).The phlogopite is enriched at the contact with the ore, and aegirine-eckermannite relatively enriched away from it.The width of the micaceous rock is variable but phlogopite at some distance from the enriched zone is still noticeable.Textural characteristics of this zone are variable,changing from a rock of alternating aegirine-eckermannite-phlogopite and cloudy feldspar (alternating without any consistency),to a mixture of all these minerals without any patterns (plate 2). Modal and chemical analyses of this zone are presented in Table 12.

5.2.3 Core Zone

Stable association: hematite-magnetite-rutile

This zone consists mainly of hematite and magnetite with subordinate phlogopite,rutile, fluorite,aegirine,eckermannite,apatite and calcite. Veinlets of calcite,barite and apatite,and veins of quartz cut the ore zones.Fluorite and barite are minor constituents associated with the ore.

TABLE 9

CHEMICAL AND MODAL ANALYSES OF THE CORE ZONE

A) Chemical Analyses (weight %)[1].

Locations	1	2	3	4	5
Fe_2O_3	89.65	91.25	86.32	88.08	89.80
FeO	6.12	6.96	5.40	6.86	7.06
TiO_2	2.81	1.76	2.86	3.17	2.34
Na_2O	0.36	0.12	0.26	–	–
K_2O	0.11	0.06	0.15	–	–
CaO	0.40	0.00	0.80	0.55	0.00
MgO	0.05	0.05	0.00	0.13	0.22
P_2O_5	–	–	–	0.16	0.00
SiO_2	0.52	0.14	0.25	–	–
TOTAL	100.02	100.34	96.04	98.15	99.32

B) Modal Analyses (volume %)[2,3]

	1	2	3
Hematite	59	60	55
Magnetite	7	8	8
Other opaques	8	5	8
Rutile	6	7	9
Fluorite	4	9	4
Aegirine	2	–	2
Phlogopite	12	11	14
Eckermanite	2	–	–
TOTAL	100	100	100

[1] Analyses 1, 2, 3 this work, 4, 5 Cirkel (1909, p. 73).

[2] Each analysis weighted to 80% opaques and rutile, 20% silicates (see text p. 41).

[3] Other opaques = oxide minerals except hem, mag. and rutile. Analyses (1, 2, 3) refer to location in Fig. 6.

TABLE 10

CHEMICAL AND MODAL ANALYSES OF HOST ROCK (BIOTITE GNEISS)*

A) Chemical Analyses (weight %)

Locations	12	13	14
SiO_2	57.67	60.20	62.46
Al_2O_3	10.47	10.83	10.22
Fe_2O_3	5.46	4.80	5.09
FeO	2.76	2.18	2.49
CaO	2.65	2.46	2.60
MgO	1.84	2.01	1.36
MnO	-	0.14	0.25
Na_2O	5.52	5.23	5.62
K_2O	9.47	10.33	10.07
TiO_2	0.17	0.20	0.36
TOTAL	96.01	98.38	100.52

B) Modal Analyses (volume %)

	12	13	14
Biotite	10	11	14
Chlorite	8	6	2
Hornblende	3	4	8
Quartz	24	25	28
K-Feldspar	40	38	36
Plagioclase	-	4	3
Hematite	13	10	7
Apatite-Rutile-Calcite	2	2	2
TOTAL	100	100	100

*Sample locations are given in Fig. 6.

TABLE 11

CHEMICAL AND MODAL ANALYSES OF THE OUTER ZONE*

A) Chemical Analyses (weight %)

Location	6	10	11
SiO_2	40.65	41.10	40.18
Al_2O_3	6.76	3.46	7.66
TiO_2	3.14	4.20	0.80
Fe_2O_3	10.36	10.11	10.64
FeO	3.49	4.26	1.12
CaO	3.42	3.84	2.76
MgO	10.64	11.72	16.25
MnO	0.08	0.15	0.14
Na_2O	8.73	10.20	14.50
K_2O	4.47	5.46	6.34
TOTAL	91.74	94.50	100.39

B) Modal Analyses (volume %)

Aegirine	34	36	42
Phlogopite	22	24	20
K-Feldspar	18	16	19
Plagioclase	7	2	3
Quartz	1	1	1
Calcite	1	1	1
Barite	1	1	1
Apatite	2	2	2
Hematite	11	14	9
Fluorite	1	1	1
Rutile	2	2	2
TOTAL	100	100	100

*Sample locations are given in Fig. 6.

TABLE 12

CHEMICAL AND MODAL ANALYSES OF THE INNER ZONE*

A) Chemical Analyses (weight %)

Locations	4	7	8
SiO_2	28.20	48.64	45.12
Al_2O_3	5.08	2.10	3.20
TiO_2	14.10	3.46	3.15
Fe_2O_3	16.46	18.75	16.42
FeO	4.12	3.26	4.12
CaO	5.49	3.46	2.05
MgO	11.27	9.49	8.75
MnO	0.19	0.00	0.15
Na_2O	1.42	2.15	4.32
K_2O	3.84	4.36	7.75
BaO	2.92	1.40	1.65
SrO	1.55	0.70	0.85
TOTAL	94.64	96.77	97.53

B) Modal Analyses (volume %)

	4	7	8
Aegirine	14	24	32
Phlogopite	7	10	12
Eckermannite	16	12	6
K-Feldspar	14	28	30
Plagioclase	6	13	10
Quartz	2	1	1
Calcite	2	1	1
Barite	2	1	1
Apatite	2	1	1
Hematite	18	6	4
Fluorite	5	1	1
Rutile	12	2	1
TOTAL	100	100	100

*Sample locations are given in Fig. 6.

It should be pointed out that the distribution of apatite, rutile, calcite, barite and fluorite are restricted to small pods or lenses. Their content in modal analyses is an approximation and does not represent an homogeneous distribution within the whole rock.

Three types of ore emplacement are recognized in the Haycock Mine property (Fig. 6):

1) shear zone emplacement (ore on slickensides); trends vary, dips vertical to subvertical.
2) small discontinuous veins and stringers cutting the foliation of the granite gneiss; trends vary, dips vertical to subvertical.
3) veins concordant with the foliation (NNE to NE vertical dip of the granite gneiss.

The largest single mass of solid hematite-magnetite, encountered during mining operations was a lens 20 metres long and at least 1 metre wide in its widest part, from which 2000 tons of high grade ore were extracted to a depth of 8 metres (Cirkel, 1909, pp. 63-72). The remains of this occurrence are now water covered.

The massive ore and most extensive fenitization is associated with the shear zone type. This zone is at maximum 20 metres wide its extent in length is undeterminable. The second and third types have similar ore mineralogy (similar core zone also). The fenites associated with these veins are much smaller. The ore veins are generally less than 0.5 meters in width. These smaller fenite zones show the disappearance of eckermannite and a marked decrease in aegirine content. On the other hand, the phlogopite content (with respect to total mineralogy) increases and in certain small veinlets is almost the only mineral of the fenite. Chemical and modal analyses of the ore zone rocks are presented in Table 9. Two analyses from Cirkel (1909, p. 73) are included for comparison.

5.2.4 Mineralogical Variation Within the Fenites

Mafic mineral distribution

Micas are of two types. Biotite is found in the paragneisses and in the meta-igneous unit and iron-rich phlogopite in the fenites. Hornblende, augite and chlorite are associated with biotite. Chlorite replaces biotite and hornblende in the surrounding rocks and they completely disappear in the outer fenite. Ore minerals decrease rapidly from the core toward the surrounding rocks. Aegirine and phlogopite have a similar distribution occurring in the two fenite zones and the core zone. The phlogopite content is greater in contact with the ore and decreases away from it. The aegirine content is normally smaller than that of phlogopite but also decreases away from the ore zone. Eckermannite occurs only in areas of intense fenitization and its content rarely exceeds aegirine or phlogopite.

Felsic mineral distribution

Primary quartz is seen in country rock where its content is about 25 percent. It disappears in the outer fenite zone.. Secondary quartz is seen as small veinlets cutting the ore zone. Feldspar from the quartzo-feldspathic gneiss is a mixture of microcline and plagioclase (An40) in the fenite zones. Plagioclase (An10) is present in area of intense fenitization.

5.3 Fenite Outside the Main Ore Zone

This second type appears in different forms. The most common is an infilling of joints, fractures and coating of slickensides with a mixture of Na-amphibole, hematite and calcite. On some slickensides the Na-amphibole occurs alone. Similarly, in some poorly foliated quartz-felspathic gneiss, Na-amphibole seems to replace the ferromagnesian minerals. Characteristic of this type of fenitization is the reddening of the affected rocks. Na-amphibole is the principal mineral on the structural surfaces; red calcite is not always present. At one location (No. 17, Fig. 6), chemical analysis (Table 5) showed the amphibole to be magnesioriebeckite. This fenite also appears as veinlets of red carbonate and red feldspar in highly brecciated quartzo-feldspathic gneiss.

The regional fenites are similar to those in other parts of the world (Deans et al., 1971). For example, the Haycock "red rock" strikingly resembles the fenites described by Heinrich and Moore (1970) from Colorado and New Mexico, U.S.A. A metasomatic origin has been tentatively proposed for such rocks, but in this particular case, obscure field relations permit no further conclusion.

5.4 Fenitization Processes: Temperature, Pressure and Oxygen Fugacity

Conditions of mineral formation including temperature, total pressure and oxygen fugacity, will be considered using chemical analyses of rocks previously presented in the Appendix. Attempts will be made to fit the data to known systems and analyse their implications.

Many detailed works are available on geothermometers in the system $FeO - Fe_2O_3 - TiO_2$, (Buddington and Vlisidis, 1955), Buddington (1956), Lindsley (1962, 1963), Buddington and Lindsley (1964), Verhoogen (1962), Vincent et al. (1957), Lindh (1972) and Haggerty & Lindsley (1970). All of these geothermometers are applicable if ilmenite and magnetite are in mutual equilibrium.

The system hematile-rutile-magnetite has not been defined and the system ilmenite-magnetite (Lindsley, 1962, 1963) was not applicable as this coexisting pair was not analysed. Therefore no PTX determination could be made with the available data.

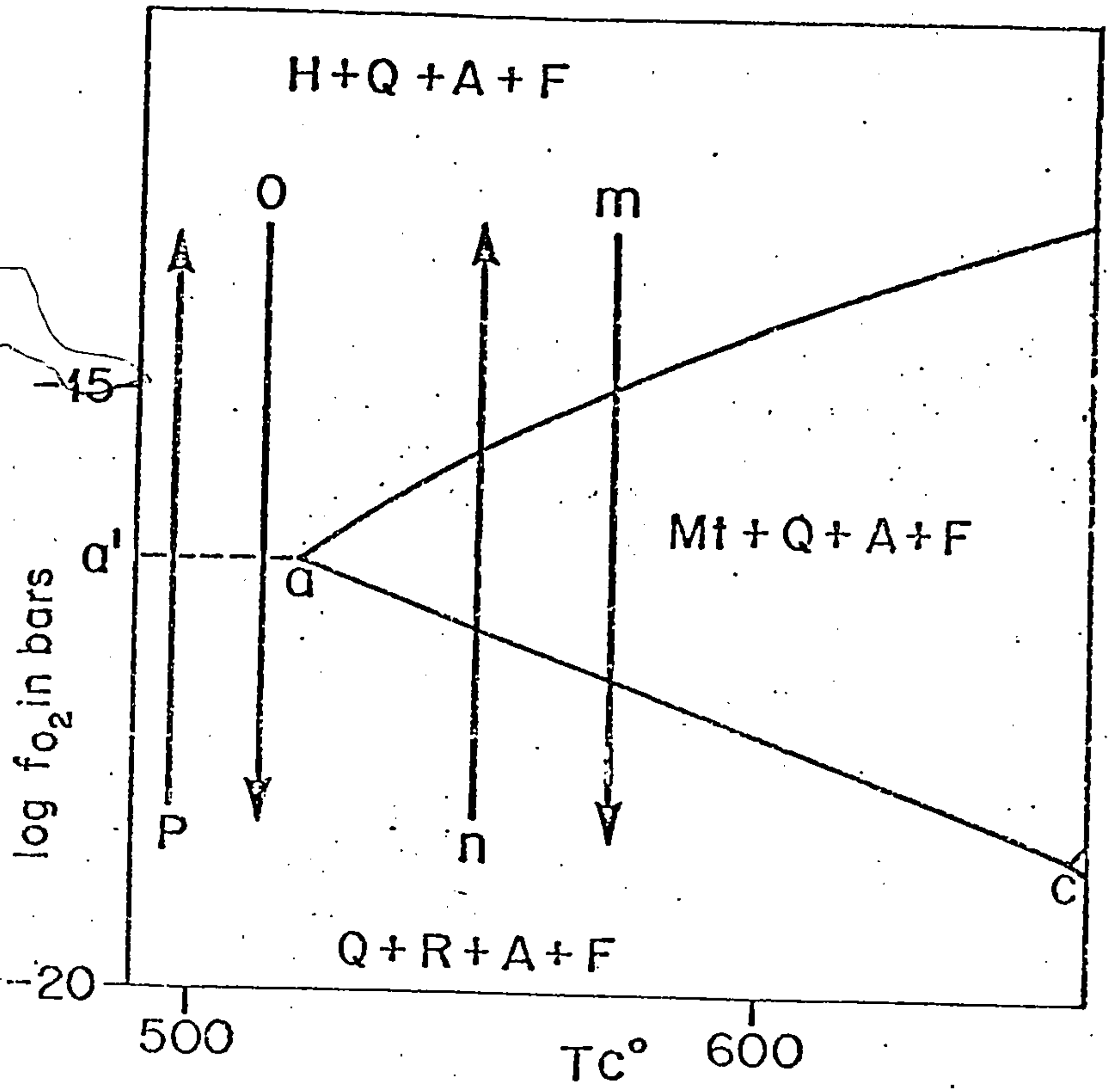

Figure 8 Phase diagram showing the possible sequence path (Ernst, 1968).
H = hematite, Q = quartz, A = arfvedsonite
F = fluid, Mt = magnetite, R = riebeckite

Silicate systems were also investigated. The mineralogy was referred to the phase diagram of Ernst (1962, 1968) involving iron oxides, riebeckite, SiO_2 and H_2O at 2000 bars fluid pressure (Fig. 8). In general, this phase diagram may be applicable to the Haycock Mine rocks and may be used as a guide to define the probable sequence of events. Assuming virtual isothermal transformations, four paths can be postulated to account for the mineral association.

m. - from hematite + aegirine passing through a magnetite + aegirine field before the appearance of riebeckite.

n. - from riebeckite + arfvedsonite field through magnetite + aegirine toward an hematite + aegirine association.

o. - directly from hematite + aegirine to riebeckite.

p. - directly from riebeckite to aegirine + hematite.

Because the association magnetite + eckermannite (arfvedsonite) is absent at the Haycock Mine, we might eliminate high temperature routes (m,n). The sporadic distribution of eckermannite suggest several fluctuations across the line A - A', and the dominance of the association hematite + aegirine suggest predominance of high oxygen fugacities.

No geothermometer appears applicable; available phase diagrams do not extend into the mineralogy under consideration. Aegirine and eckermannite were examined which, because of their restricted occurrences, might be helpful in formulating a model of formation.

Aegirine in fenite can be formed by at least two different processes.

a) metasomatically by reaction of sodium and iron with quartz and the co-precipitation of iron oxides. Metasomatic aegirine was produced by Sieber and Freeman (1968) and is described by the following equation:

$$Na^{1+} + Fe^{3+} + 3SiO_2 \rightarrow NaFeSi_2O_6 + Si^{4+}.$$

b) reaction of alkalic-silicic solutions with magnetite or hematite.

Reaction *a* is at equilibrium at 485°C at a total pressure of 50 bars. From petrological evidence it is seen that at the Haycock Mine aegirine is always associated with hematite suggesting a related origin. Aegirine and hematite could be hydrothermal products (shown by the syntheses of Ernst, 1968) and/or could have been metasomatically produced: eg. the metamorphism of iron formation, in a high oxidation, low temperature environment (postulated by Ernst, 1968).

Phase diagrams for eckermannite are not available although the mineral was synthesized but found unstable in the range of temperature and pressure studied (Phillips and Rowbotham, 1968). However, alkali amphibole (crocidolite, the fibrous form) is commonly associated with hematite in iron formations in South Africa, Australia, India, Bolivia and USSR. Most authors believe that certain "layers of the original iron formation were peralkaline, hence compositions were appropriate for crystallization of members of the riebeckite-magnesioriebeckite series" (Ernst, 1968, p. 98). In these iron formations, the association hematite + crocidolite is an indication of high oxidation and low temperature.

This chapter has outlined several mechanisms to explain the origin of the Haycock ores and fenites. There is no uniquely applicable system, and parts of several theories may be combined as will be attempted in the following chapter. It should be pointed out that there is some restriction to any conclusion owing to the fact that chemical analyses variations are in some cases drastic. Especially in the case of K_2O where comparison of the same zone (outer) from one area to the other shows a difference in the order of 10 per cent. No explanation is proposed but detailed microprobe analyses within zones and on different zones would provide more data for an answer.

CHAPTER 6

CONCLUSION

From the evidences derived in earlier chapter the Haycock fenites could have formed by two different mechanisms: (1) Introduction of material emanating from plutonic rock or (2) Mobilization of elements from an iron-rich strata.

Basically, four elements need to be concentrated: iron, sodium, titanium and magnesium. According to option 1, these elements would have been supplied by the intrusive and concentrated along fracture surfaces. In option 2, these elements would be present in the original rocks and concentrated through an isochemical transformation. Fracture surfaces would favor this transformation.

Examples for the first model are the alkalic metasomatites of the Great Glen Fault area in Scotland (Deans et al., 1971). These fenites are the result of the metasomatic transformation by alkaline solutions which emanated from some unknown source (presumably a carbonatite magma at depth) on the adjacent country rocks. In these cases an alignment of fenites would be possible.

A theory embodying parts of option 1 and option 2 has been proposed by Eliseev et al. (1961) for certain deposits at Krivoi Rog, USSR and Glagolev (1966) at Kurst, USSR. These authors propose alkalic metasomatism, associated with granitic or syenitic magma, reacting with an iron formation to produce a fenite aureole.

Option 2 implies that an iron rich horizon, such as an iron formation be remobilized. Effects of thermal metamorphism would probably aid this remobilization.

Since the Haycock deposits do not involve large amounts of iron (a few thousand tons of hematite-magnetite at most) the source could be an iron formation, an iron-rich sedimentary layer. Although these iron-rich rocks may be of igneous origin, the sedimentary origin is favoured.

There are two points that favour an iron-rich strata (option 2): 1) the alignment of the iron deposits of the general area (occurrences 2 to 6 in Fig. 1), approximately parallel to the regional foliation as discerned from Wilson's map (Wilson 1920) and 2) lack of a suitable igneous intrusive which could have provided the required materials. Quite possibly the deposits are linked to an intrusion hidden at depth, although there is absolutely no evidence for it. On this basis, option 2 is favoured.

Burial at moderate depth, low to moderate temperature, thermal metamorphism and growth of new minerals (aegirine and eckermannite) in a solid state or through the agency of solutions would facilitate the mineralogical geochemical changes including the oxidation of iron. Sodium, titanium and magnesium elements concentrated with respect to the surrounding gneisses, may have been present in the original layer or they may have migrated from nearby wallrocks to form new minerals.

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APPENDIX 1

A.1 METHODS

Minerals and rock analyses included, electron microprobe, wet chemical methods (atomic absorption, spectrophotometer), optical absorption spectroscopy, Mössbauer resonance studies and X-ray diffraction. Methods and instruments will be described.

A.1.1 Electron Microprobe Methods

Two different instruments were used. First silicates and carbonates were analysed at McGill University with the acton electron microprobe by Tarig Ahmegdali in May 1973. The data were processed using version VII of the Empadr computer program originally written by J.C. Rucklidge and E.L. Gasparrinni (1962). A specimen current of 30 nanoamperes and a voltage of 15 kV were used throughout the analysis. Standards were McGill internal standards: Aegirine 23, Amphibole 202, and Anorthite 205. Their chemical analyses are given in Table 13. Two grains per mineral per section were analysed. On each analysis, 5 shots were made on each grain, 2 grains for each mineral were analysed for each polished thin section.

Analyses of magnetite, hematite and rutile were made at Carleton University on a Cambridge MK5 electron microprobe by Mrs. Penny Morton in December, 1974. Data were reduced with a version of Rucklidge program modified by Watkinson and Mainwaring (October, 1972). The sample current was 30 nanoamperes with 15 KV acceleration voltage. Standards used for calibration and their analyses are given in Table 13. In addition, pure iron was used as an iron standard at Carleton University, in the microprobe analyses of rutile and opaque minerals.

A.1.2 Wet Chemical Analysis Method

Wet chemical analyses were made with the atomic absorption apparatus Tectron A.A. and Unicam series 2 Spectrophotometer. Both types of analyses were made using standard methods used in the Geochemical laboratory of the Geology Department of the University of Ottawa and is described below.

A schematic diagram outlines the various steps of analysis for different elements (Fig. 9). Rocks were analysed by using internal standards and calibrated against USGS rock standards.

The hydrofluoric-perchloric acid attack on rocks is a standard method consisting in mixing rock powders with acid until a solution is produced. Solution is affected with different steps of cooling and remixing

TABLE 13

INTERNAL STANDARDS USED FOR MICROPROBE ANALYSES

(element weight %)

	AMP 202(1)	ANOR 205(1)	AEGIRINE 23(1)	RUTILE (2)
Na	1.21	6.11	8.37	
Mg	5.23	0.01	0.85	
Al	6.40	10.81	0.83	
Si	19.70	30.88	24.18	
K	0.76	2.91	0.28	
Ca	8.26	0.56	1.83	
Ti	0.56	-	0.79	59.68
Mn	0.49	-	0.16	
Fe	14.81	0.16	20.13	0.02
Ba	-	0.13	-	
Sr	-	0.33	-	
O	42.90	47.98	42.58	41.30
TOTAL	100.32	99.88	100.00	101.00

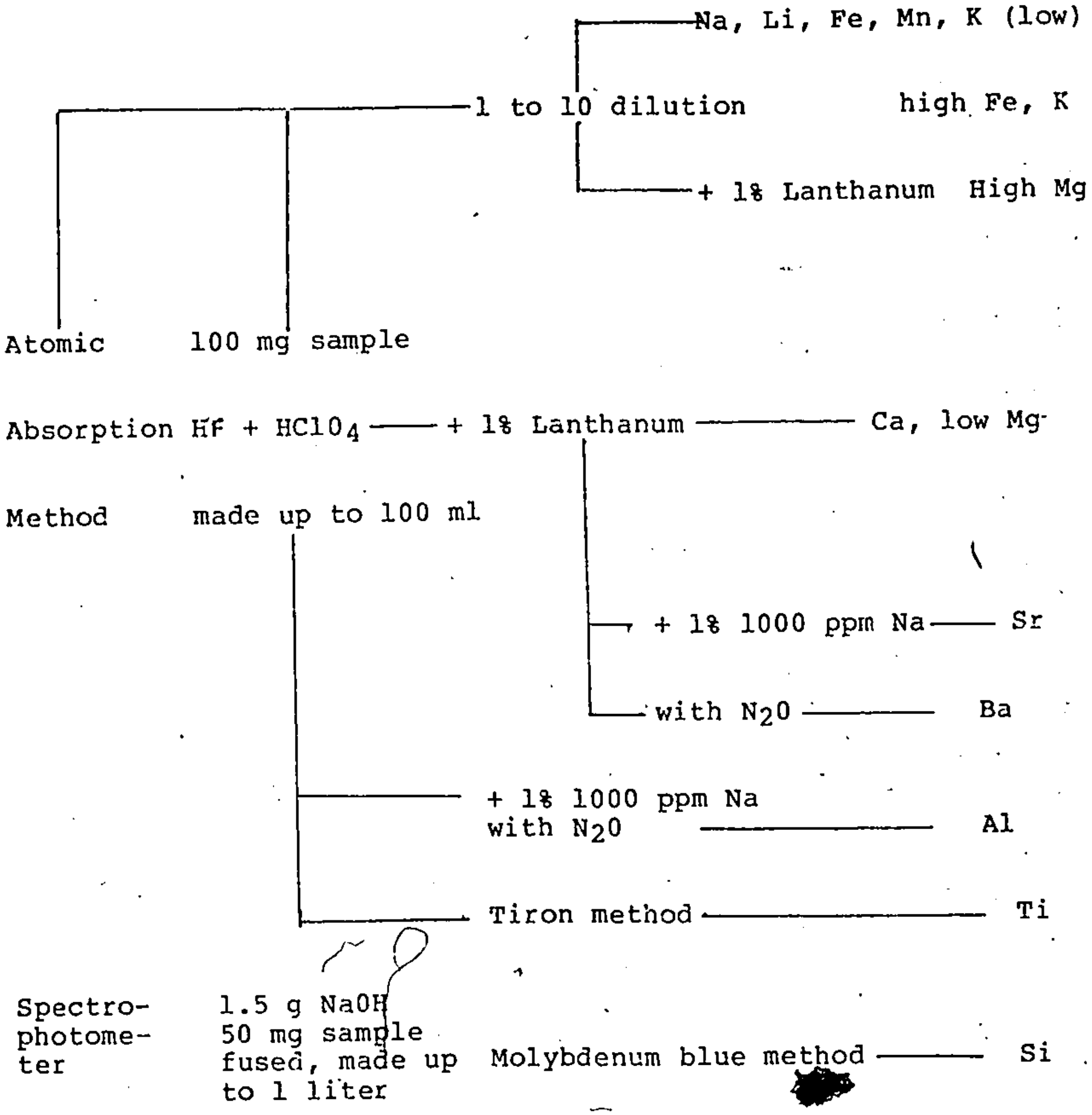
(1) Internal Standards: McGill University, Montreal, Quebec.

(2) Internal Standards: Carleton University, Ottawa, Ontario.

FIGURE 9

SCHEMATIC DIAGRAM FOR

CHEMICAL ANALYSES



with acid. Values of atomic absorption and spectrophotometer were calibrated with known standards, and calibration curves for different elements were used to derive analysed proportions. Fe^{+3} and Fe^{2} were resolved using method of Jen (1973).

A.1.3 Mössbauer Analysis

The Mossbauer effect may be defined as the recoil-free emission and resonant absorption of nuclear γ rays in solids. It can provide information on the magnitude and symmetry of the crystal field at the lattice site, the number of non-equivalent sites occupied by the nuclear isotopes, the site population, oxidation state and ordering of the isotopes in complex crystal structures. Mössbauer analyses were done at the Mossbauer Laboratory at the Mines Branch, Department of Energy, Mines and Resources, Ottawa, under the direction of Dr. M.G. Townsend. Co^{57} in copper was used as γ ray source. The samples were crushed to 250 to 300 mesh and a cake of 2.5 cm diameter and about 1 mm thickness was then fixed in a slot of a brass plate to fit the Mössbauer apparatus. The sample was run for 3 hours at room temperature (25°C). Energies were resolved utilizing the Doppler effect, and analysed by a Univac computer program, available at the Mines Branch, EMR, Ottawa.

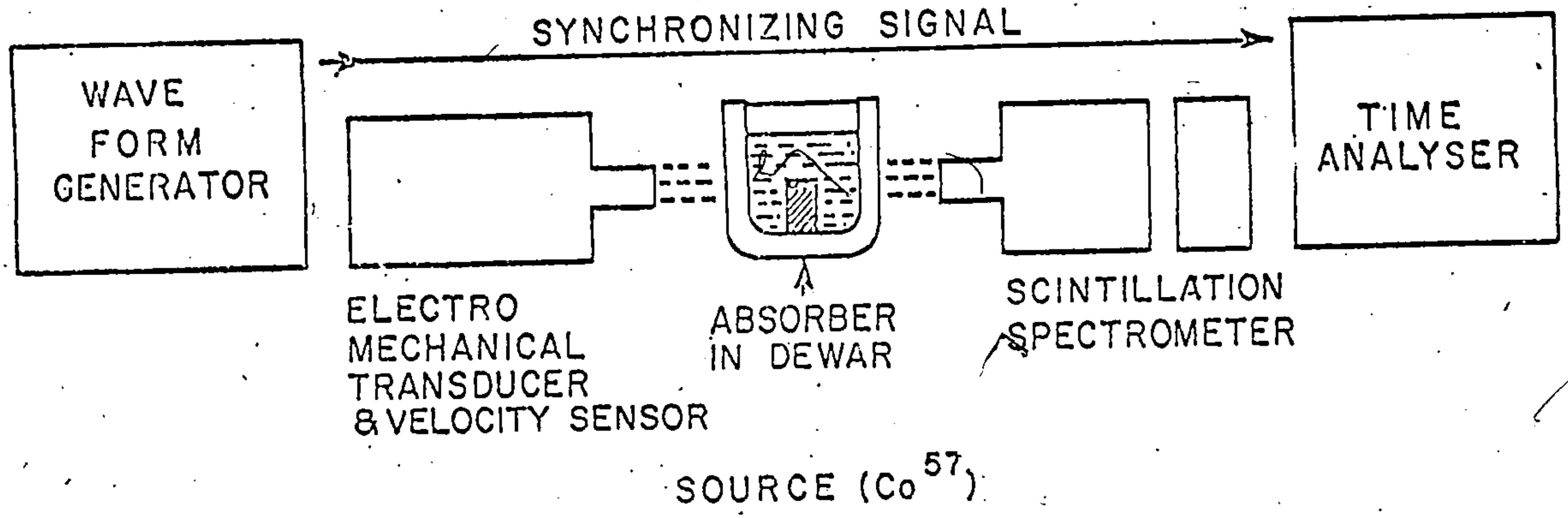


Figure 10 Diagram of instrument set up for Mössbauer experiment.

A.1.4 Optical Absorption Spectroscopy

When light is passed through a mineral containing transition metal ions with unfilled 3d shells (the most widespread is iron), it causes certain wavelengths to be selectively absorbed, resulting in an observed colour in transmitted light. The cause of this absorption is the excitation of electrons between th split 3d orbital energy levels and electron transitional between ions. In the present case, a polished thin section (*a* - *c* or X - Z plane), 0.02 mm thick, of an aegirine crystal 4.5 cm long and 1 cm wide was used. The specimen was run on a Cary, model 14 spectrophotometer by Dr. P.G. Manning, Inland Waters Branch, Environment Canada, Ottawa. Two different spectra (polarized and unpolarized light) were collected from each specimen. The spectra were plotted as absorbance against wave number on the step charge recorder.

A.1.5 X-ray Camera and Diffractometer

Mineral identifications were made by x-ray powder camera (57.3 mm diameter) and x-ray diffractometer. The Ievens-Straumanis film-mounting method was used with x-ray photographs. The x-ray tubes had copper and iron targets and nickel and manganese filters depending on the mineral analysed.

APPENDIX 2

A.2 RESULTS

A.2.1 Optical Spectroscopy of Aegirine

Aegirine ($NaFe^{+3}Si_2O_6$) spectra are shown in Figs. 11 and 12 and a qualitative energy-level diagram for a $3d^5$ ion in octahedral and tetrahedral field in Fig. 12.

The free ion spectroscopic studies place the ^4G state 32,600 cm^{-1} above the ground state. In a crystal field, the energies of the Russell-Saunders states are always lowered, hence the Fe^{+3} transition $^6A_1 \rightarrow {}^4A_1{}^4E(G)$ should be observed below 32,000 cm^{-1} (Manning, 1972), in this case octahedral Fe^{+3} transition is seen at 22,880, 22,830, 22,800 cm^{-1} in Fig. 10. It compares to 22,700 cm^{-1} in andradite (Manning, 1967). This feature (22,800 cm^{-1}) is identified on the basis of its sharpness. Sharp bands are typical of field independent transitions. Note in Fig. 12 that the feature around 22,800 cm^{-1} has 2 components reflecting the slight separation of the $4A_1(G)$ and $^4E(G)$ levels (Fig. 13). These two components are typical spectra of an octahedral Fe^{+3} field-independent transition (Manning, 1967). The unresolved peaks near 22,800 cm^{-1} (4500 A) were noted by Schuller (1958) who

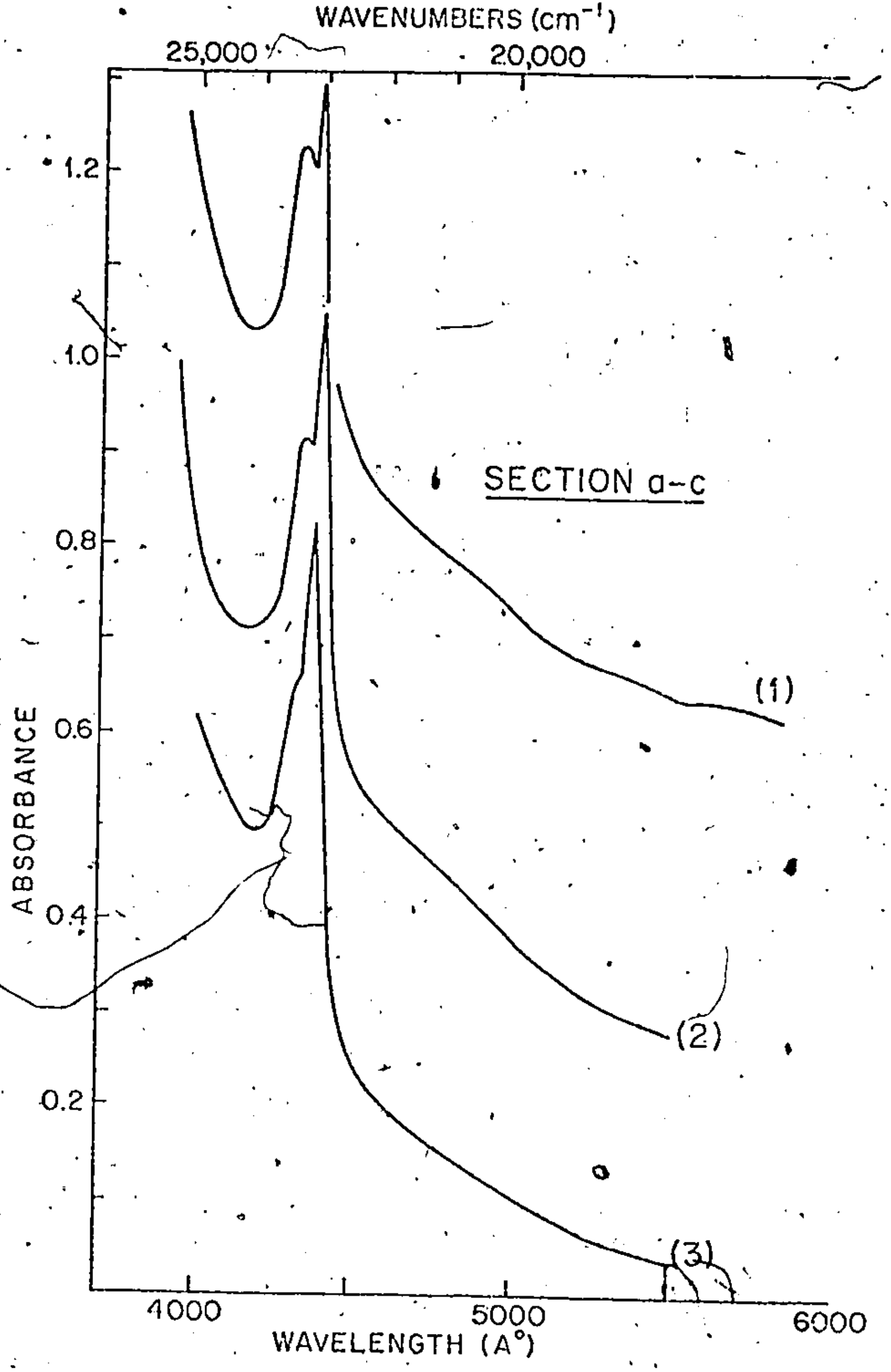


Figure 11 Spectra of aegirine, (Sp) Section a-c (1) polarised E ∥ c, (2) unpolarized, (3) polarized E ∥ a. Specimen Hay-2 from location 1 in Fig. 6.

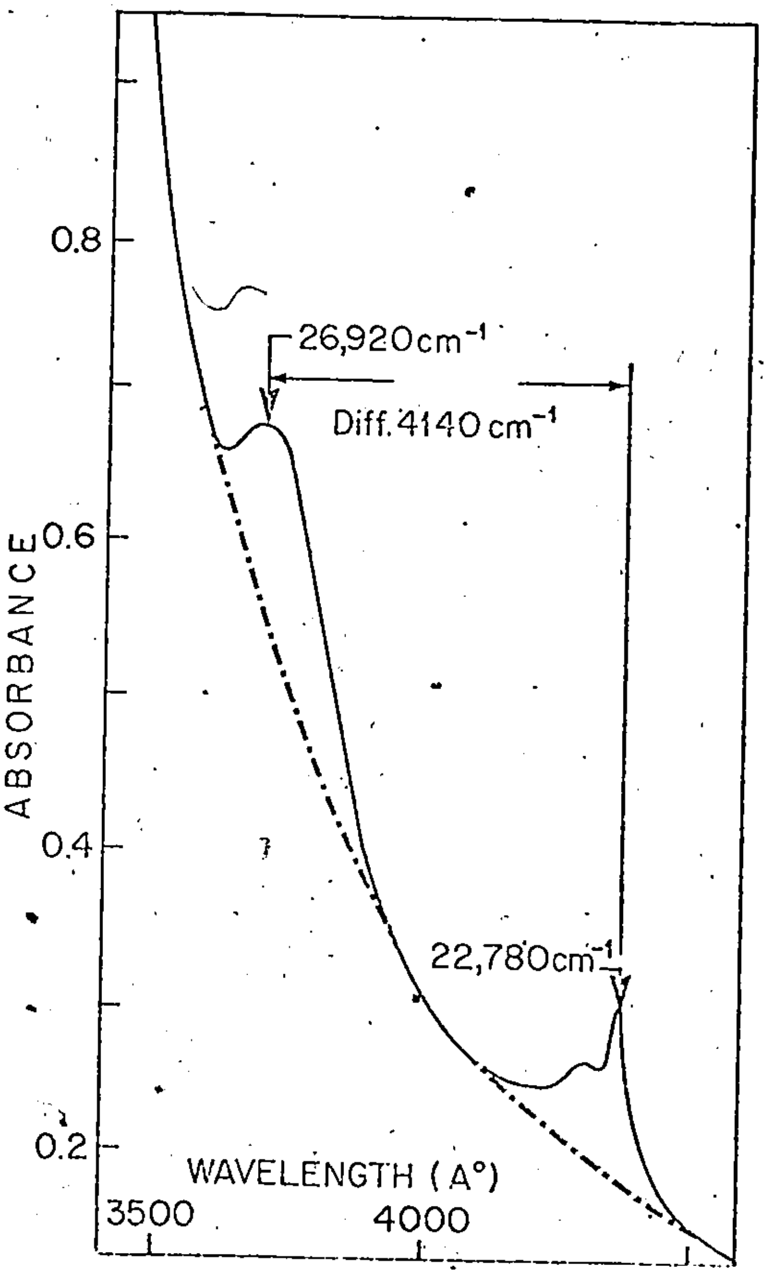


Figure 12. Spectra of aegirine, (Sp) Section a-c unpolarized spectra of aegirine. Specimen Hay-2, location 1 in Fig. 6.

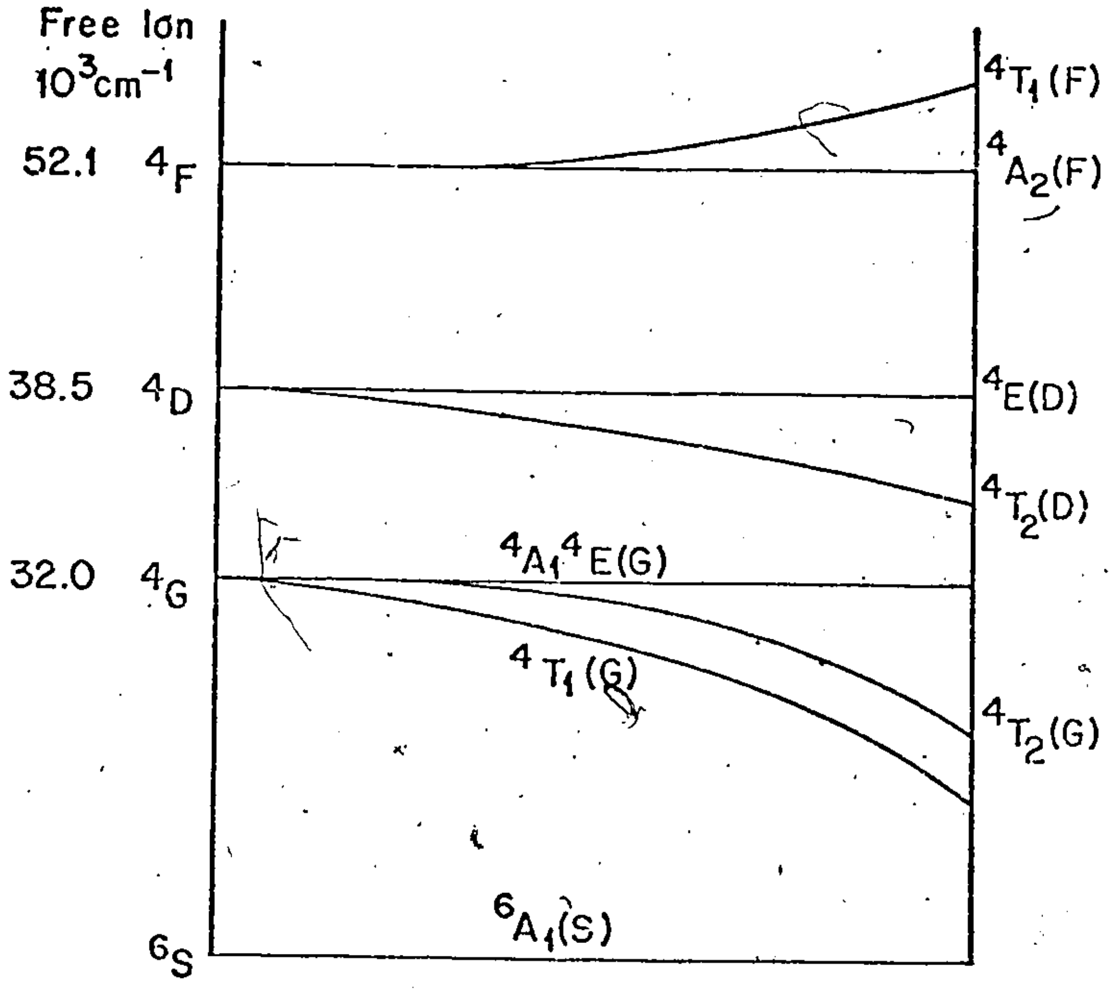


Figure 13 ENERGY LEVEL DIAGRAM FOR $3d^5$

ascribed them to a $Fe^{+3} \rightarrow Fe^{+2}$ electron transfer but multiplicity of peaks and their sharpness argue against this conclusion.

Note also in Fig. 12 the second absorption band at 26,920 cm^{-1}. This band is due to transition (octahedral Fe^{+3}) to the field independent $^6A_1$ $^4E(D)$ levels (Manning, 1968).

A.2.2 Mössbauer Study of Aegirine

Mössbauer spectra of aegirine is shown in Fig. 14 and data summarized in Table 14. The two inner peaks are assigned to Fe^{+3} in M (1), an octahedral site with δ_{eq} = 0.205 mm/sec = 0.328 mm/sec.

Observations and interpretations of the Mossbauer spectra yield the following conclusions.

(1) No hyperfine splitting was observed, indicating that aegirine is a paramagnetic solid.

(2) Isomer shifts are shown in Table 14. The iron in aegirine is in the high spin ferric state in M(1) and M(2) (8-fold site) is assigned to Na^+ (Clark *et al*., 1969).

(3) Quadrupole splittings are shown in Table 3a, they show that probably both M(1) and M(2) are distorted.

The resolution of the spectra is insufficient to make further conclusions.

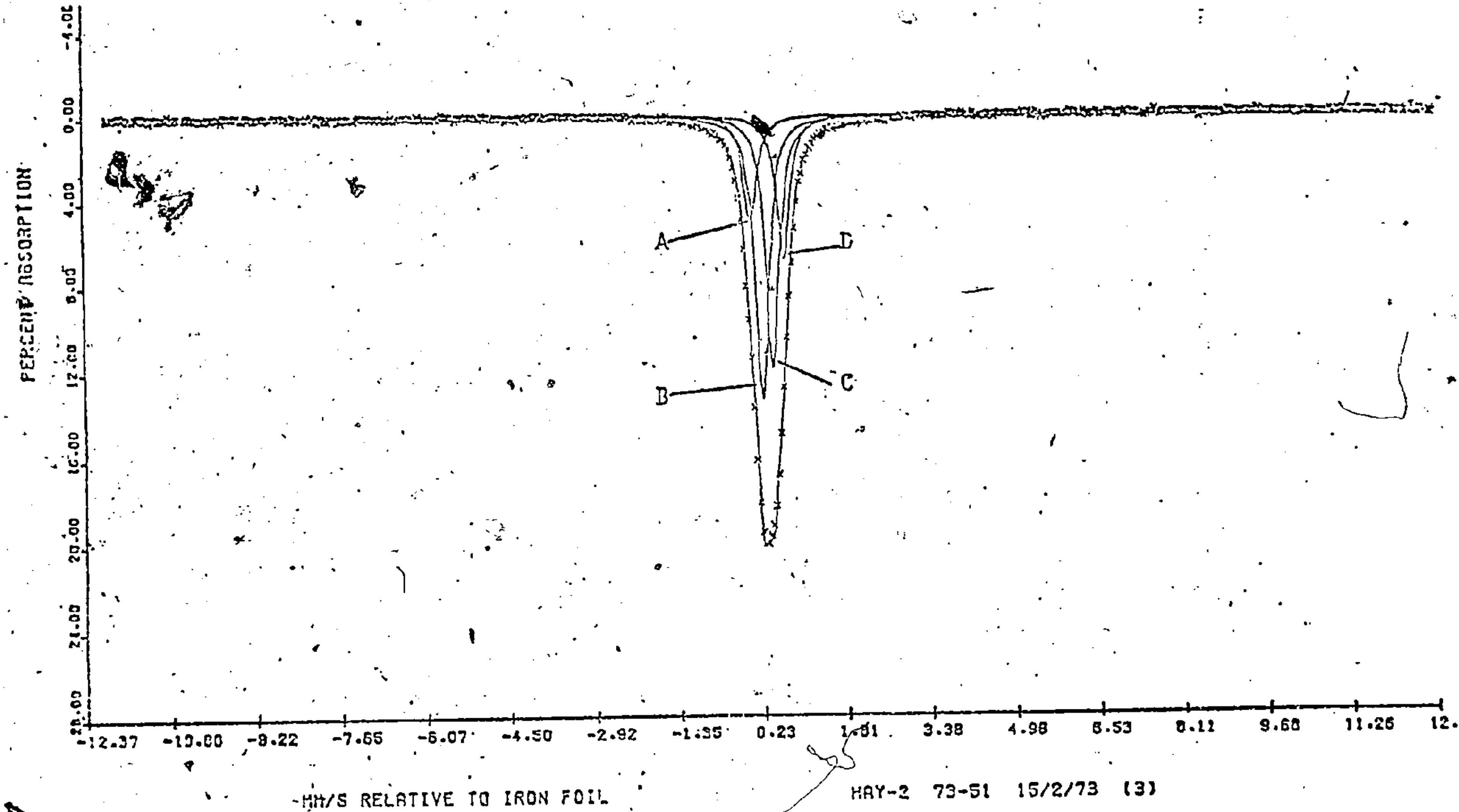


Figure 14. Mössbauer spectra of aegirine .Source Co^{57} in Cu. Specimen Hay-2 from location 1 in Fig. 6.

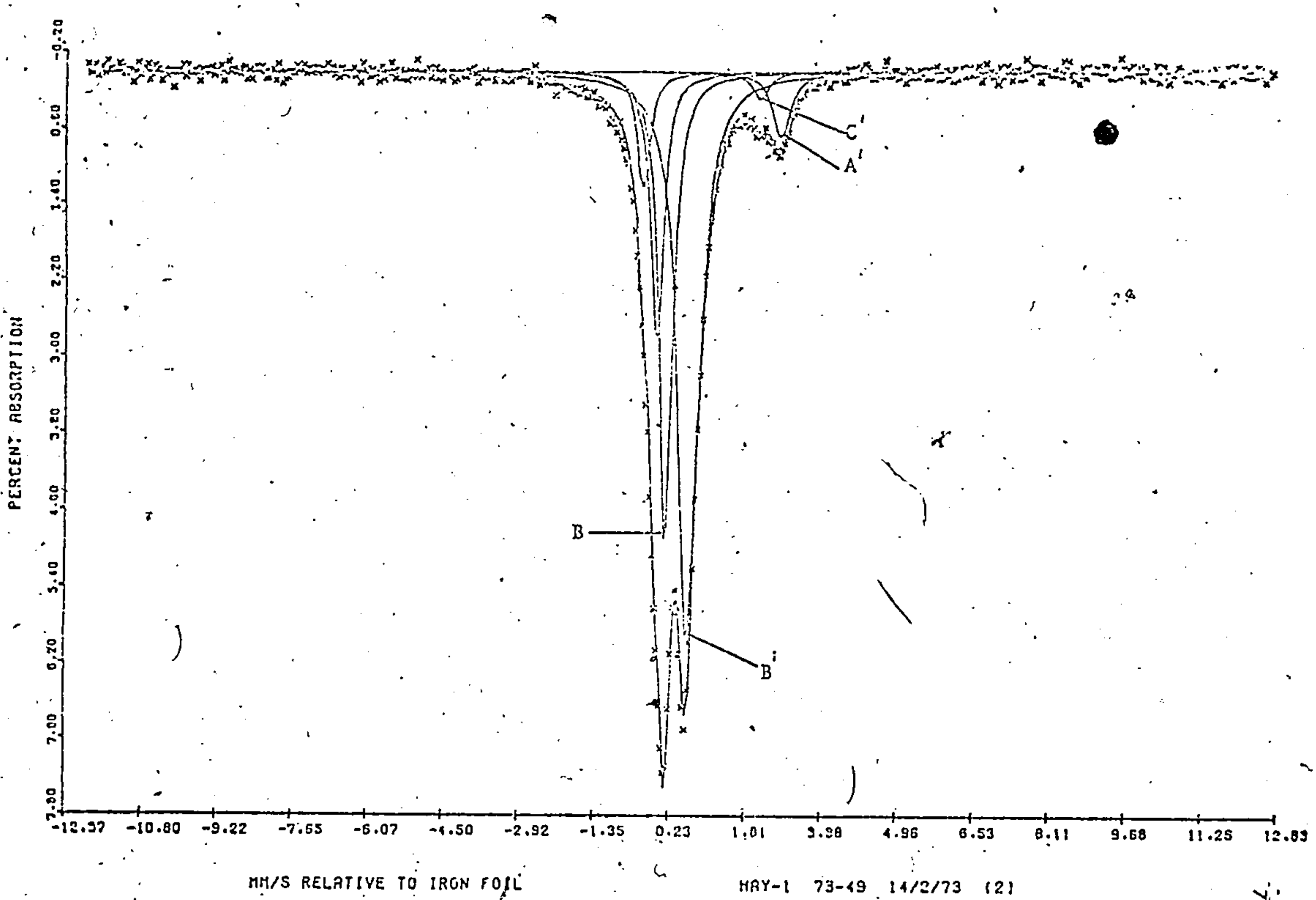


Figure 15 Mössbauer spectra of Eckermannite. Source Co^{57} in Cu.
Specimen Hay-1 from location 1 in Fig. 6.

A2.3.1 Mössbauer Study of Eckermannite

Mössbauer spectra of eckermannite is shown in Figure 15 and results are summarized in Table 14. The variations in the values of quadrupole splitting may reflect the degree of distortion in octahedra around transition elements (Hafner, 1968). Site allocations are as follows:

Fe^{+2} in M(1) with δ_{eq} = 2.856 mm/sec,
= 1.074 mm/sec
Fe^{+3} in M(2) with δ_{eq} = 0.445 mm/sec,
= 0.370 mm/sec
Fe^{+2} in M(3) with δ_{eq} = 2.142 mm/sec,
= 0.994 mm/sec

As the refinement of the spectra is incomplete further conclusions would be only tentative. It is worthwhile noting the similarities of the spectra of this eckermannite and the magnesium crocidolite of Bancroft and Burns (1969), where spectra were refined more extensively.

TABLE 14

MÖSSBAUER RESONANCE PARAMETERS FOR AEGIRINE AND ECKERMANNITE

AEGIRINE

	POSITION mm (sec)	CHEMICAL SHIFT (θ, mm/sec)	QUADRUPOLE SPLITTING (δeq, mm/sec)	COUNT x 10^7
A	0.014	0.319	0.608	0.13
B	0.226	0.328	0.205	0.35
C	0.431			0.31
D	0.623			0.18

ECKERMANNITE

	POSITION mm (sec)	CHEMICAL SHIFT (θ, mm/sec)	QUADRUPOLE SPLITTING (δeq, mm/sec)	COUNT x 10^7
B	-0.077	0.994	2.142	0.11
C'	0.593			0.37
B	2.066			0.01
C	2.502			0.04

APPENDIX II

CHEMICAL ANALYSES OF ROCKS OUTSIDE THE COMPLEX (Location in Figure 6) AND X-RAY AND DIFFRACTOMETER DATA

Mineral assemblages of samples used in chemical analyses. Samples are located in Figure 6.

Locations 1 to 9 refer to mining pits or trenchs at the Haycock mine and are compatible with Cirkel's (1909) numbering system. Locations 10 to 17 refer to sampling sites which show a representative rock related to that specific rock unit.

Locations 1 to 5 are the best examples of where a core zone can be found. Locations 4, 7, 8 show the best of the inner zone and similarly at locations 6, 10 and 11 are well developed outer zones. Locations 12, 13 and 14 were sampled and analysed as host rock (biotite gneiss). Locations 15 to 17 as country rock. Location 4 has the best example of the presence of the core and inner zone within a small area. It has been analysed for core and inner zones chemically, and recorded under the same location number.

Location:

1 - This location represents the most complete example of the core zone. The rock is about 80% ore minerals and the rest consists of aegirine, eckermannite, phlogopite, apatite and quartz. The rock is cut by late veins of calcite with minor barite and hematite. The chemical analyses for aegirine, eckermannite, microcline and phlogopite are from the same sample. This sample was chosen for its most complete

mineralogy and its proximity to the ore sample. The ore sample was chosen for freshness. It was collected about 1 metre away from the inner zone sample. The calcite veinlet from which the samples was chosen is about 5 metres away from the ore sample. The veinlet is 0.2 metre thick.

2 - This location was (with number 1) one of the two largest pits of the mine. This location belongs to the core zone. A block sample about 1 to 2 kg was chemically analysed. A polished thin section was obtained from a sample which showed larger aegirine crystals. From the same section microcline was analysed.

3 - This area is characterized by numerous veinlets of calcite. It belongs to the core zone and has been analysed for whole rock from a sample cored 2.5 cm in width and 10 cm in length.

4 - Location 4, as previously defined, has been analyzed for whole rock for both core and inner zone. A small calcite vein was sampled and calcite has been analysed. The core zone in this area is fairly restricted (0.1 metre in width and extends for about 20 metres). It consists of ore minerals (100%). On each side of this zone, the inner zone is large, in some instances up to 5 metres. It consists in large proportion of phlogopite (80%), aegirine and microcline being minor.

5 - Similarly to location 3, this location is a small area of the core zone. It was sampled for whole rock chemical analysis of the core zone from a cored sample. This area is cut by a

vein of calcite. One polished section from one vein was analysed for calcite. No inner zone has been identified near this core zone.

6 - Location 6 is near the east end of the mine property. It does not contain any large amount of ore minerals and is considered outside of the complex. It consists of a prominent outcrop of syenitic gneiss. A core (2.5 cm by 10 cm) was analysed. No separate mineral analyses were performed at this location.

7 - Location 7 is best described as an adit. It does show a large amount of phlogopite. The eckermannite sample used in Mössbauer analysis was collected in this location. A large block was collected for whole rock analysis. From the same block a polished thin section was obtained, and microprobe analysis was performed on microcline and phlogopite.

8 - This area is a small isolated outcrop of the inner zone. It does not contain any veins of calcite. It is rich in aegirine and phlogopite. Only a whole rock chemical analysis was performed on this sample.

9 - This area is a trench which was cut during the mining operation. The well developed inner zone is lensoid. Eckermannite, microcline and phlogopite (the main mineral) have been chemically analysed. Also a whole rock analyses was performed on a 2 kg sample.

10 and 11 - Both of these locations are in syenitic gneiss with superimposed fenite effects. These fenites belong to the outer zone and have been chemically analysed. Aegerine and phlogopite are common but the rock retains evidence of its primary minerals.

12, 13, 14, 16 and 17 - These locations belong to the granite and syenite gneiss unit. They show no or minor trace of fenitization except for filling of the different structures. Location 17 is characterized by a large amount of fibrous magnesioriebeckite. All of these locations have been chemically analysed. At location 17 the magnesioriebeckite was separated and chemically analysed and it was also X-rayed.

15 - This area is where the carbonate rock was found. This rock contains calcite, dolomite and barite. It contains also minor magnetite and is bright red. The outcrop is rather small (5 m x 3 m) and field relationship difficult to establish. The outcrop is now buried under a house basement.

TABLE 15

WALL ROCK CHEMICAL ANALYSES AREA 17 (Fig. 6)

Location	17A	17B	17C	17D	17E
SiO_2	56.49	51.28	67.70	67.30	62.04
Al_2O_3	17.59	15.08	10.92	14.91	13.79
FeO*	13.69	8.19	7.05	4.66	6.60
MgO	5.85	8.50	4.46	4.03	7.88
CaO	2.39	11.18	0.66	3.55	1.88
Na_2O	0.56	2.11	0.91	4.90	4.39
K_2O	3.55	1.00	7.13	2.10	2.38
MnO	0.18	0.10	0.06	0.04	0.05
TOTAL	100.30	97.44	98.89	101.49	99.01

TABLE 16

WALL ROCK CHEMICAL ANALYSES AREAS 13, 14, 16, (Fig. 6)

Location	13	14	16A	16B
SiO_2	70.20	62.38	60.35	61.20
Al_2O_3	11.80	14.82	12.10	9.88
FeO*	4.27	8.64	7.53	7.25
MgO	2.63	4.63	7.34	7.29
CaO	1.59	2.83	6.46	8.49
Na_2O	3.19	3.28	4.03	2.66
K_2O	4.45	0.05	2.41	2.05
MnO	0.05	-	0.10	0.10
TOTAL	98.18	99.20	100.32	99.02

*Total iron expressed as FeO.

TABLE 17

X-RAY DATA FOR AEGIRINE

$2\theta^{\circ}$	d(A°)	I
17.50	6.36	100
25.49	4.39	60
26.25	4.26	10
31.10	3.61	10
33.65	3.35	30
34.25	3.28	10
34.70	3.24	15
35.50	3.17	35
36.45	3.09	05
37.85	3.06	80
39.05	2.89	100
40.60	2.79	05
41.60	2.72	05
44.80	2.54	15
45.05	2.52	20
46.20	2.46	35
50.90	2.25	05
52.30	2.19	10
54.45	2.11	50
55.15	2.09	15
57.50	2.04	15
58.55	1.98	05
60.20	1.93	10
62.00	1.88	05
64.30	1.82	05
65.05	1.80	20
68.30	1.72	30
74.05	1.60	25
75.08	1.58	30
78.40	1.53	20
78.80	1.52	15
82.75	1.46	15
88.05	1.39	15
96.35	1.29	10

Film 72-295, Radiation CuKα, Filter Ni
Diffractometer 74-33, Radiation FeKα, Filter Mn
Specimen Location 1 in Fig. 6.

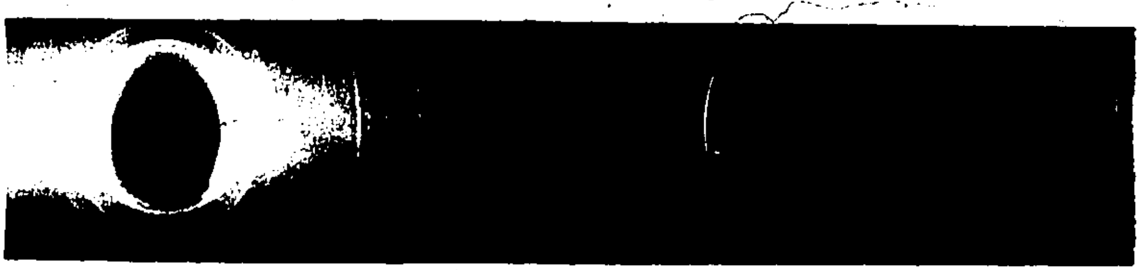


Plate I. X-ray diffraction photograph of aegirine.
Cu/Ni, Camera dia. 57.3mm.
Specimen No: OP 1, location 1, Fig. 6.

TABLE 18

X-RAY DATA FOR ALMANDINE

2θ°	d(Å)	I
26.65	3.34	05
31.00	2.88	60
34.75	2.58	100
36.50	2.46	10
38.15	2.35	20
40.05	2.25	10
43.10	2.09	05
44.60	2.03	05
48.75	1.86	20
55.30	1.86	10
57.80	1.59	60
60.20	1.53	80
64.85	1.43	10
73.65	1.28	10
75.80	1.25	20

Film 74-006, 74-10, 74-16

Radiation CuKα

Filter Ni

Specimen Location: OP-2, in contact with marble zone, northeast corner Fig. 3.
Almandine from Biotite Gneiss.

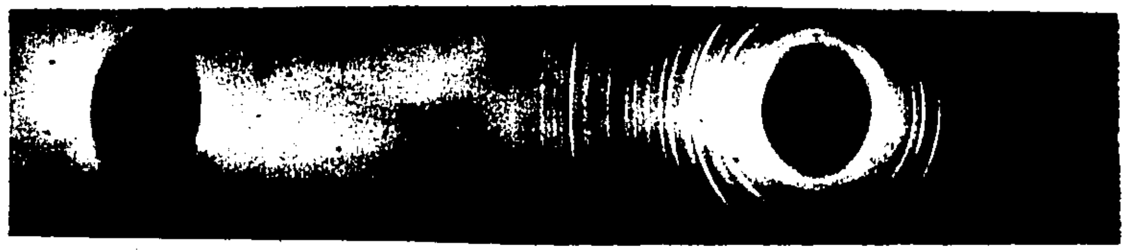


Plate II. X-ray diffraction photograph of almandine.
Cu/Ni Camera dia. 57.3mm.
Specimen No:OP 2
Location:near northeast corner of Fig.3.

TABLE 19

X-RAY DATA FOR BARITE

$2\theta^{\circ}$	d(Å)	I
25.15	4.44	10
25.85	4.33	15
28.75	3.90	25
29.65	3.78	10
31.45	3.57	50
32.75	3.43	80
34.00	3.31	50
36.40	3.10	45
40.00	2.83	25
41.65	2.72	25
46.10	2.47	05
49.35	2.32	05
49.70	2.30	05
50.30	2.27	05
52.00	2.20	10
54.45	2.11	30
55.90	2.86	25
56.25	2.05	10
60.30	1.92	10
63.80	1.83	05
65.45	1.79	05
66.95	1.75	05
70.80	1.67	05
72.45	1.63	05

Diffraction:74-1 Radiation: FeKα, Filter: Mn
Specimen Location 15 in Fig. 6.

TABLE 20

X-RAY DATA FOR CALCITE

$2\theta^\circ$	$d(A^\circ)$	I
23.00	3.86	10
29.25	3.05	100
31.30	2.85	05
35.75	2.51	30
39.40	2.28	50
43.10	2.09	40
47.30	1.92	80
48.55	1.87	70
57.65	1.59	10
60.70	1.52	20
64.70	1.44	10
65.80	1.41	10
70.80	1.33	10
73.00	1.29	10

Film 72-294, 72-298

Radiation $CuK\alpha$

Filter Ni

Specimen Location 2 in Fig. 6.

Plate III. X-ray diffraction photograph of calcite.
Cu/Ni Camera dia. 57.3mm.
Specimen from location 4 in Fig. 6.

TABLE 21

X-RAY DATA FOR MAGNESIO-RIEBECKITE

2θ°	d(A°)	I
12.25	9.07	15
13.20	8.42	80
22.80	4.90	10
24.75	4.51	20
28.90	3.88	05
33.00	3.41	15
34.50	3.26	20
36.30	3.10	50
38.15	2.96	10
40.60	2.79	10
41.80	2.71	40
43.90	2.59	10
44.95	2.53	10
49.40	2.31	10
49.95	2.29	05
50.70	2.26	05
53.10	2.16	10
57.25	2.02	05
65.20	1.79	05
71.85	1.65	05
75.25	1.58	05

Diffractometer: 74-2, 72-26, 72-297

Radiation: FeKα

Filter: Mn

Specimen Location 17 in Fig. 6.

Plate IV. X-ray diffraction photograph of magnesio-riebeckite.Cu/Ni Camera dia. 57.3 mm. Specimen from location 17 in Fig. 6.

TABLE 22

X-RAY DATA FOR MICROCLINE

2θ°	d(A°)	I
21.05	4.22	20
22.45	3.96	05
23.45	3.89	30
25.50	3.53	20
27.20	3.27	100
29.80	2.99	30
30.85	2.89	20
32.35	2.76	10
34.85	2.57	40
41.70	2.16	05
44.00	2.05	10
46.15	1.96	10
50.55	1.80	50

Film 72-303

Radiation: CuKα

Filter: Ni

Specimen Location I from Fig. 6.

TABLE 23

X-RAY DATA FOR SILLIMANITE

2θ°	d(A°)	I
17.70	5.01	05
19.70	4.50	05
20.80	4.27	10
24.25	3.67	20
26.65	3.34	100
27.70	3.22	05
29.05	3.07	10
35.85	2.50	40
38.20	2.35	20
39.85	2.26	05
41.30	2.18	10
45.25	2.00	05
50.20	1.81	70
54.90	1.67	20
60.00	1.54	70
61.90	1.49	05
68.10	1.36	80

Film 74-3

Radiation: CuKα

Filter: Ni

Specimen Location: 200 m southwest of Location 12 in Fig. 6.

Plate V. X-ray diffraction photograph of sillimanite.
Cu/Ni Camera dia. 57.3mm.
Specimen: OP-5
Location:200 metre southwest of No. 12.

PLATE VI

Photomicrograph, in polarized light, magnification X 25, showing difference in texture (small scale feature) from crystalline (phlogopite^P, microcline), to banded (aegirine^A, hematite) to fibrous (eckermannite^E).

Location 3 Fig. 6


P
E
A

PLATE VII

Photomicrograph in unpolarized
light, magnification X 25 of sample
from the outer zone.
Location 11 Fig. 6
P = phlogopite
M = microcline

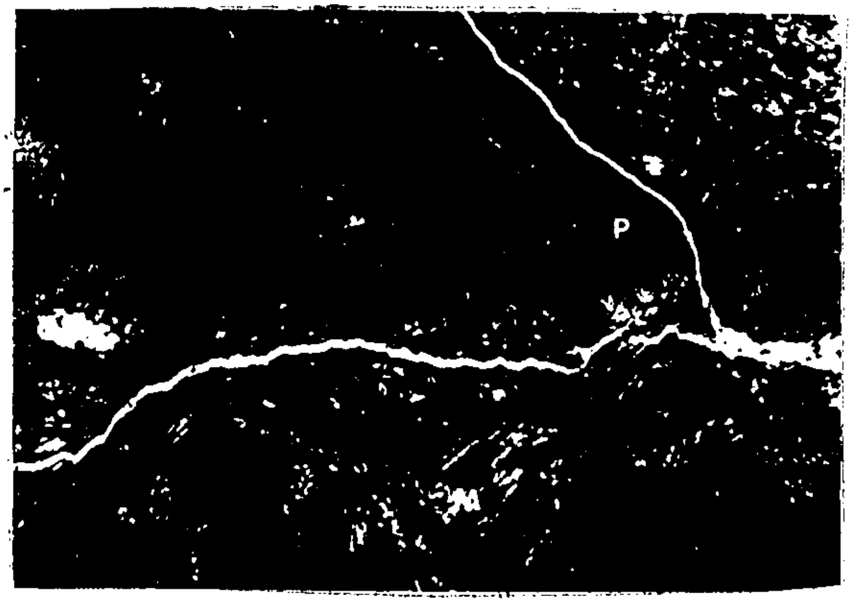

P

PLATE VIII

Photomicrograph, unpolarized light, magnification X 25, showing phlogopite^{P} and aegirine^{A} in hematite^{H}-magnetite^{M}.

Location 2 Fig. 6


H
P
M