# OCCURRENCE AND ORIGIN
# OF GARNET
# IN THE
# SOUTH MOUNTAIN BATHOLITH

Honours Bachelor Thesis
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Dalhousie University
Barry Allan

DEPARTMENT OF GEOLOGY
DALHOUSIE UNIVERSITY
HALIFAX, NOVA SCOTIA
CANADA
B3H 4J1

DALHOUSIE UNIVERSITY, DEPARTMENT OF GEOLOGY

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**Author:** Barry ALLAN

**Title:** OCCURRENCE AND ORIGIN OF GARNET IN THE SOUTH MOUNTAIN BATHOLITH

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# ABSTRACT

Garnet occurs around the margin of the South Mountain batholith as an accessory mineral in three distinct comagmatic phases. Electron microprobe analyses and textural relationships of 50 garnet-biotite pairs indicates that garnet had two origins. Garnet associated with xenoliths in biotite granodiorite or monzogranite are interpreted as being metamorphic in origin, and garnet from the goundmass of monzogranite and leucocratic monzogranite aplite are considered to be primary.

## Table of Contents

## Chapter 1 INTRODUCTION

### 1.1 Introduction

out of place

General interest in garnet began in the early 1800's (Hisinger, 1817), but it was 1915 before any work on its crystallography and classification was published (Ford, 1915). Research continued through the 1920's and 1930's with infrequent descriptions of the occurrence, properties and chemical compositions of garnets. Late in the 1940's renewed interest led to a steady flow of information about ~~their~~ its origin and stability in different environments. The intense activity in this field still persists today.

Barrow --

Garnet has frequently been used as an indicator of metamorphic grade (Atherton and Edmund, 1966; Engel and Engel, 1960). It is an essential mineral of high pressure eclogite facies rocks (Bloxham, 1959) and an accessory mineral in ultramatic f complexes (Pabst, 1936; Levin, 1950) and acid igneous rocks (Pabst, 1938, Oliver, 1956). Its presence often carries some significant information about a rock type's genetic origin and conditions during crystallization.

X
X

## 1.2 The Object of the Study

In the South Mountain batholith of southwestern Nova Scotia (McKenzie and Clarke, 1975), garnet occurs as an accessory mineral. The presence of this phase has commonly been recorded, but the chemical and textural relationships ~~they~~ it bears with separate granitic phases in the batholith, or the chemistry of garnets themselves, is unknown.

Using garnets from eight localities, involving four distinctly different, but comagmatic phases of the batholith, (it is the purpose of) this thesis attempts to shed some light on this problem. Of particular interest is the interpretation of garnets which occur in granitic liquids.

## Chapter 2 PUBLISHED INFORMATION

X

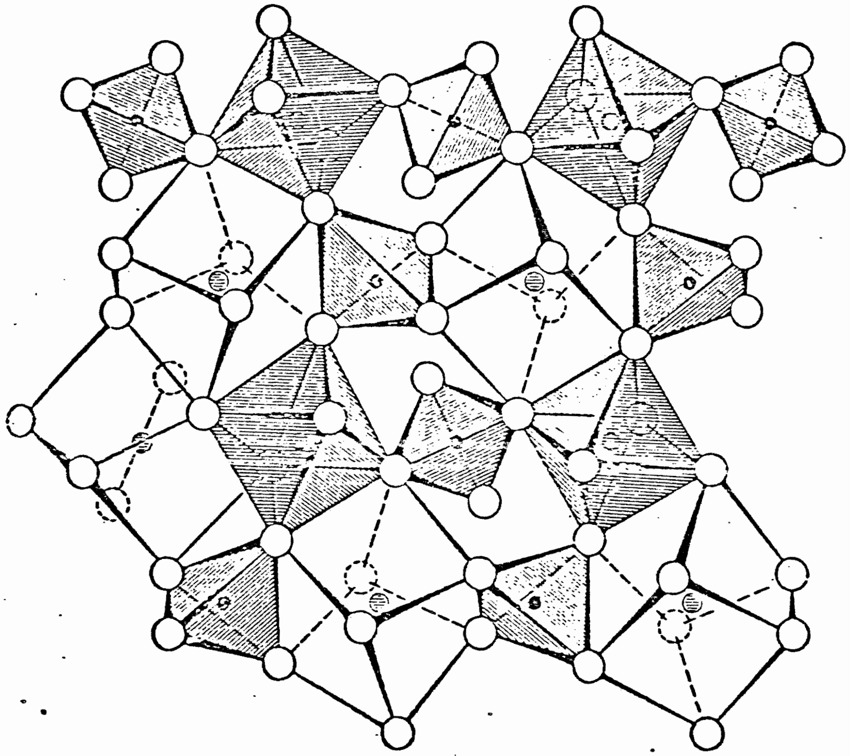
### 2.1 Chrystal Chemistry

Section 11 [illegible]

The garnet group belongs to the nesosilicate class of minerals and is represented by the generalized formula $X_3Y_2(SiO_4)_3$; where X is a divalent cation in 8-fold coordination and Y is a trivalent cation in 6-fold coordination.

Garnets crystallize in the cubic crystal system (space group la3d: a = 11.5-12.5Å), with a density range of 3.4-4.3 g/cc and a relatively high refractive index (n = 1.79-1.94); the hardness is 6.5-7.5. When rare earth varieties are included, garnets can exhibit any colour of the visible spectrum (Deer et al, 1967).

In the garnet structure, a silicon-oxygen tetrahedron exists as an independent group linked to the octrahedra of a trivalent ion, while a divalent metal ion is situated in the interstices of the Si-Al network - each metal ion being surrounded by eight oxygens (Fig. 1). The usual coordination number of $Fe^{2+}$, $Mg^{2+}$, $Ca^{2+}$ and $Mn^{2+}$ with oxygen is 6(Ra/Rc = .46-.57), but in garnet they are in 8-fold coordination. Although five species of garnets are most common, hypothetically there could be sixteen since one of four trivalent ions ($Fe^{3+}$, $Al^{3+}$, $Cr^{3+}$, $Mn^{3+}$) may combine with any one of the four divalent ions. Rare substitutions can also occur such as small amounts of titanium for aluminum (Deer et al, 1967). The garnet group itself is subdivided according to the dominant divalent and trivalent ion (Fig. 2). Generally 99% of all garnets can be considered as consisting of almandine ($Fe^{2+}$), pyrope ($Mg^{2+}$), spessartine ($Mn^{2+}$), grossular ($Ca^{2+}$) and andradite ($Ca^{2+}$, $Fe^{3+}$) (Novak and Gibbs, 1971).



Portion of the garnet structure projected down z showing the framework of alternating tetrahedra and octahedra (shaded portion) and the 8-fold triangular dodecahedra coordinating the {X} cations. The triangular dodecahedra are drawn as distorted cubes. Large open circles represent oxygens, smaller ones the [Y] cations, solid circles the (Si) cations, and the hatched ones the {X} cations.

Fig. 1

| *Pyralspite* | | *Ugrandite* | |
|---|---|---|---|
| Pyrope | MgAl | Uvarovite | CaCr |
| Almandite | FeAl | Grossularite | CaAl |
| Spessartine | MnAl | Andradite | CaFe |

[6] N. H. Winchell and A. N. Winchell, *Elements of Optical Mineralogy.* John Wiley and Sons, New York, 1927.

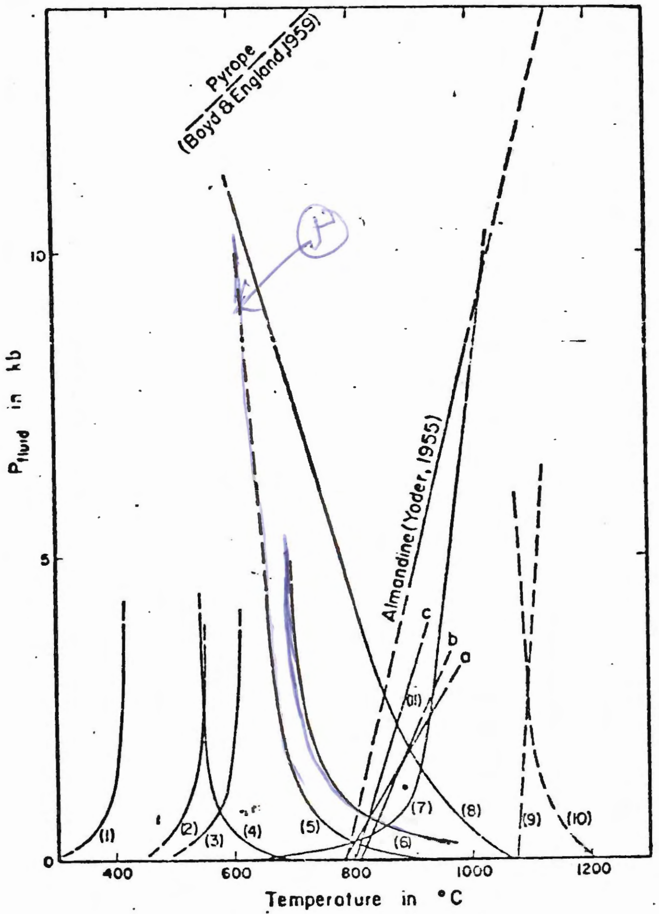
Fig. 2

$Al^{3+}$ is the most common trivalent ion of the garnet framework, but limited amounts of $Fe^{3+}$, $Cr^{3+}$ and $Mn^{3+}$ can substitute into the octahedral site. Of the divalent ions, Zenman (1962) suggested that $Fe^{2+}$ and $Mn^{2+}$ are more easily accommodated into an $Al_2Si_3O_{12}$ framework than a slightly too small $Mg^{2+}$ ion or the especially large $Ca^{2+}$. Green (1977) supplemented this further by showing that garnet crystallization at low temperatures preferred $Mn^{2+}$ to $Fe^{2+}$. If any cation other than $Ca^{2+}$, $Fe^{2+}$, $Mg^{2+}$ or $Mn^{2+}$ substitutes into the 8-fold position, there would be structural instability of the garnet (Novak and Gibbs, 1971).

Finally, in a crystallizing magma where silicon and oxygen are the major components, the first silicate to cool usually has the $Si^{4+}$ ions as widely spaced as possible. This occurs when oxygen touches only one silicon ion (forming the $SiO_4$ tetrahedron) and each $SiO_4$ tetrahedron is separated by a metal cation. The resulting crystal structure is a unit in the silicate class - the nesosilicates (Dana, 18th edition).

## 2.2 Stability

Cooes (1955) produced synthetic almandine, spessartine, grossular and pyrope at 900°C. He found that almandine and spessartine formed at 10 Kilobars pressure, but grossular and pyrope needed pressures of 20 and 30 Kilobars respectively to be stable. Yoder's (1955) work on the stability range of almandine produced an equilibrium curve (Fig. 3). More recent

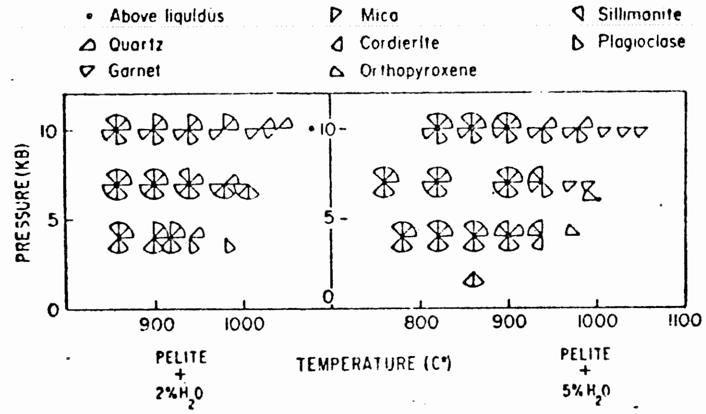


$P_{\text{fluid}}$-$T$ plot of various reaction curves of synthetic minerals and melting of magmas.

(1) Manganese chlorite + quartz = spessartine + fluid
(2) Iron chlorite + quartz = almandine + fluid (IQF buffer)
(3) Iron chlorite + quartz + magnetite = almandine + fluid (FMQ buffer)
(4) Beginning of melting of pegmatite (Jahns & Burnham, 1958)
(5) Beginning of melting of granite (Tuttle & Bowen, 1958)
(6) Crystallization of granite (Jahns & Burnham, 1958)
(7) Beginning of crystallization of amphibole from olivine tholeiite (Yoder & Tilley, 1962)
(8) Beginning of melting of olivine tholeiite (Yoder & Tilley, 1962)
(9) Hypothetical melting curve of anhydrous basalt (Yoder & Tilley, 1962)
(10) Hypothetical melting curve of spessartine (water saturated)
(11) Almandine stability curves: (*a*) buffered by IQF; (*b*) buffered by IW; (*c*) buffered by WM.

Fig. 3

work by Green (1976) showed garnet to crystallize from a pelitic liquid at conditions as low as 820°C temperature and 7.0 Kilobars pressure (Fig. 4).



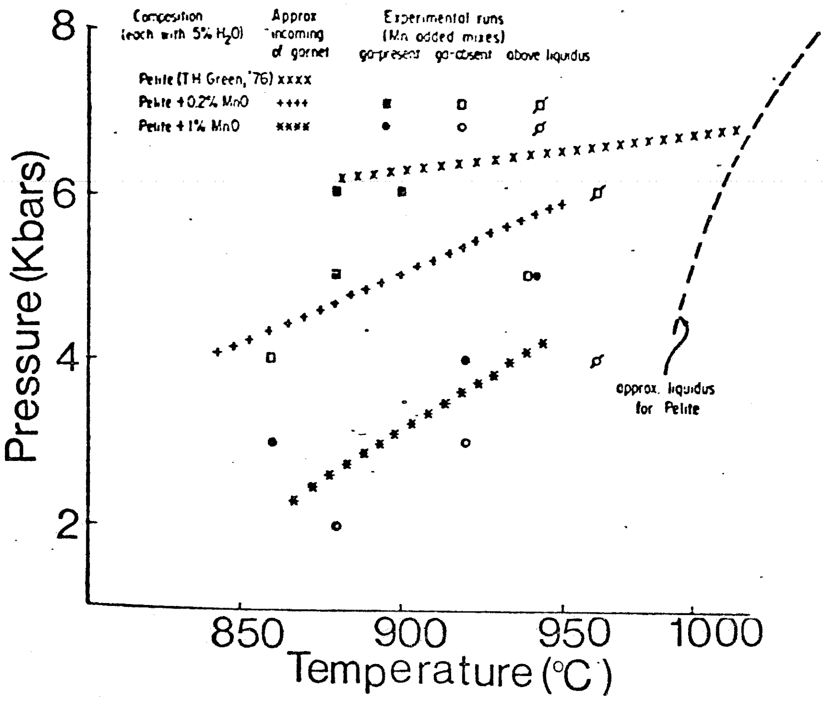
Results of experimental runs on pelite + 2 percent $H_2O$ and pelite + 5 percent $H_2O$.

Fig. 4

Additional experiments by Green (1977) showed that garnets with greater than 10% spessartine could be produced from pelitic melts slightly enriched in manganese, at less than 850°C and 7.0 Kilobars pressure (Fig. 5).

Hsu (1968) experimentally demonstrated that the stability field of almandine was strongly decreased by an increase in oxygen fugacity (Fig. 3), whereas the stability field of spessartine was independent of oxygen fugacity. He was also able to produce synthetic spessartine at lower temperatures (Fig. 3).

Green (1976) concluded from his experiments that an increase in water activity decreased the stability field of garnet. However, in later work



Stability of Garnet With MnO Enrichment

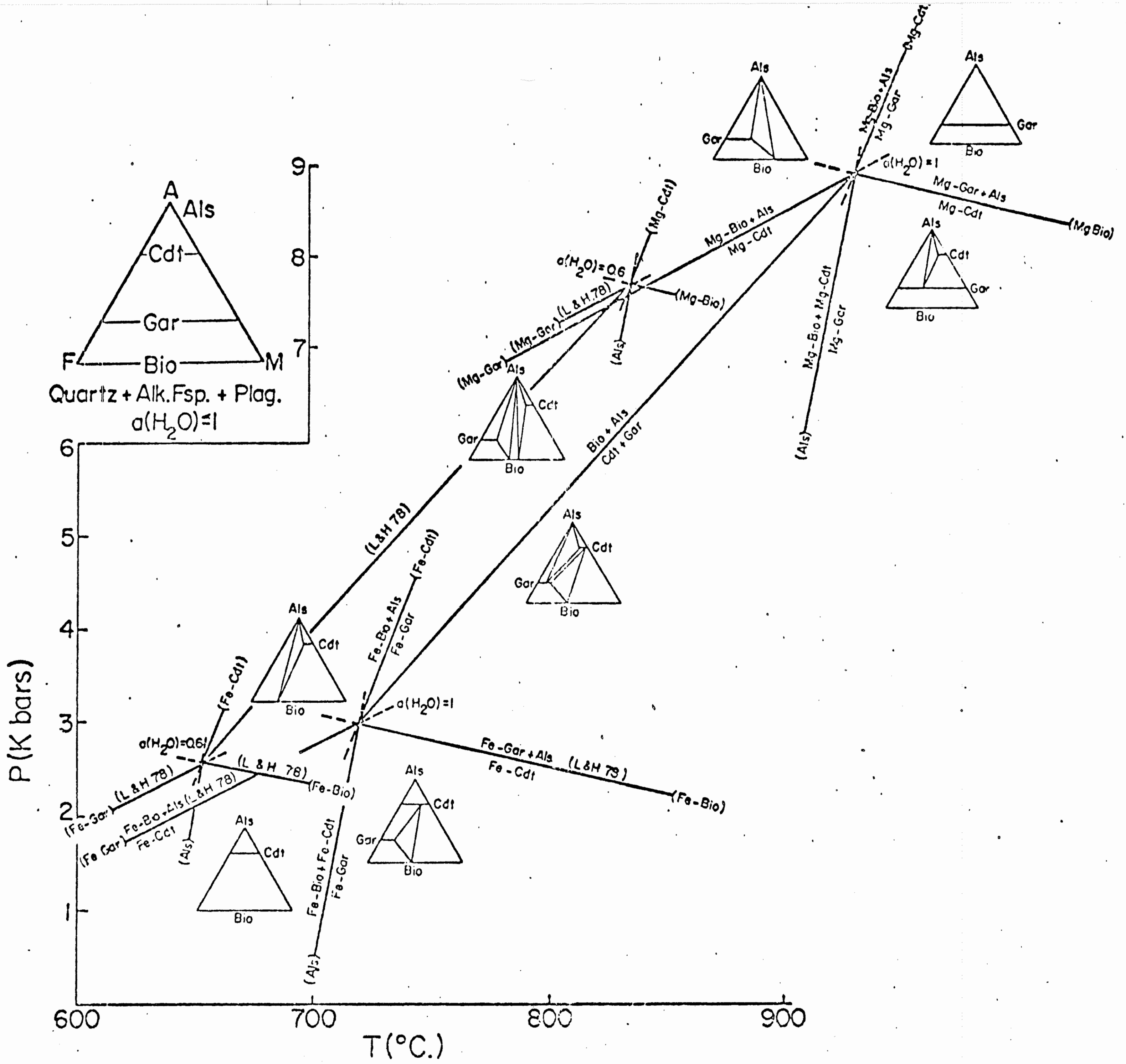
Fig. 5

by Green (1977), the stability of garnet was shown to be more dependent on temperature and composition, than the activity of water.

The process of magma differentiation involves decreasing temperatures, reduction of the amount of liquid and change in composition of liquid with time. The differentiated liquid has an increased Mn/(Fe + Mg) ratio and a higher silica concentration (Goldschmidt, 1954). The enrichment of manganese in a silica rich liquid may allow the magma to approach the stability field of spessartine and stabilize Mn rich garnet (Green, 1977).

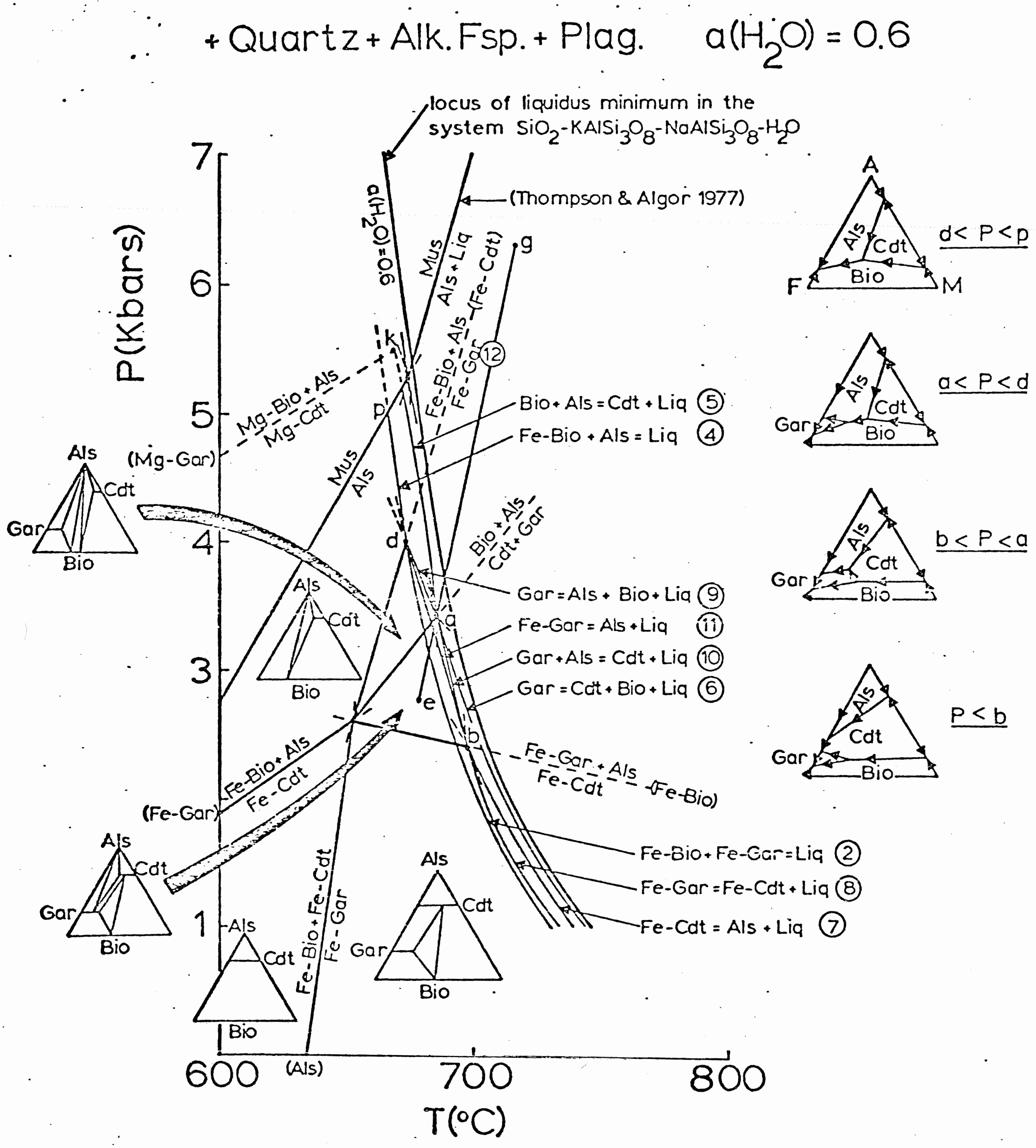
Pyrope and gorssular content may reflect either original concentrations in the liquid, or high temperature and pressure conditions of garnet~~s~~ stabilization (Green, 1976).

For the South Mountain batholith, Abbott and Clarke (1978) have postulated a hypothetical stability field of garnet (and its co-existing AFM minerals) in a silicate~~-~~melt which is saturated with respect to quart~~s~~z, two feldspars and biotite, at two different activities of water ($A(H_2O)$ = 0.6 and 1.0; Fig. 6). On this stability diagram, they have superimposed the solidus curve for a granitic liquid, producing diagrams which show~~n~~ the stability field of garnet and its co-existing AFM minerals in a granitic liquid (Fig. 7 and 8). They suggest that the portion of the stability field which applies to the South Mountain batholith is represented by the AFM liquidus relationship depicted ~~in~~ by emng of Fig. 9.



Hypothetical Relationships for P-T Conditions of South Mountain Batholith

Fig. 6



+ Quartz + Alk. Fsp. + Plag.
a($H_2O$) = 0.6
locus of liquidus minimum in the system $SiO_2$-$KAlSi_3O_8$-$NaAlSi_3O_8$-$H_2O$
(Thompson & Algor 1977)
P(Kbars)
7
6
5
4
3
1
600
700
800
(Als)
T(°C)
a($H_2O$)=0.6
Mus
Als + Liq
Fe-Bio + Als
Fe-Gar
(Fe-Cdt)
g
k
p
d
a
b
e
12
Mg-Bio + Als
Mg-Cdt
(Mg-Gar)
Mus
Als
Bio + Als
Cdt + Gar
Bio + Als = Cdt + Liq ⑤
Fe-Bio + Als = Liq ④
Gar = Als + Bio + Liq ⑨
Fe-Gar = Als + Liq ⑪
Gar + Als = Cdt + Liq ⑩
Gar = Cdt + Bio + Liq ⑥
Fe-Bio + Als
Fe-Cdt
(Fe-Gar)
Fe-Gar + Als
Fe-Cdt
(Fe-Bio)
Fe-Bio + Fe-Gar = Liq ②
Fe-Gar = Fe-Cdt + Liq ⑧
Fe-Cdt = Als + Liq ⑦
Fe-Bio + Fe-Cdt
Fe-Gar
Als
Cdt
Gar
Bio
A
F
M
d< P<p
a< P<d
b< P<a
P < b

Fig. 7

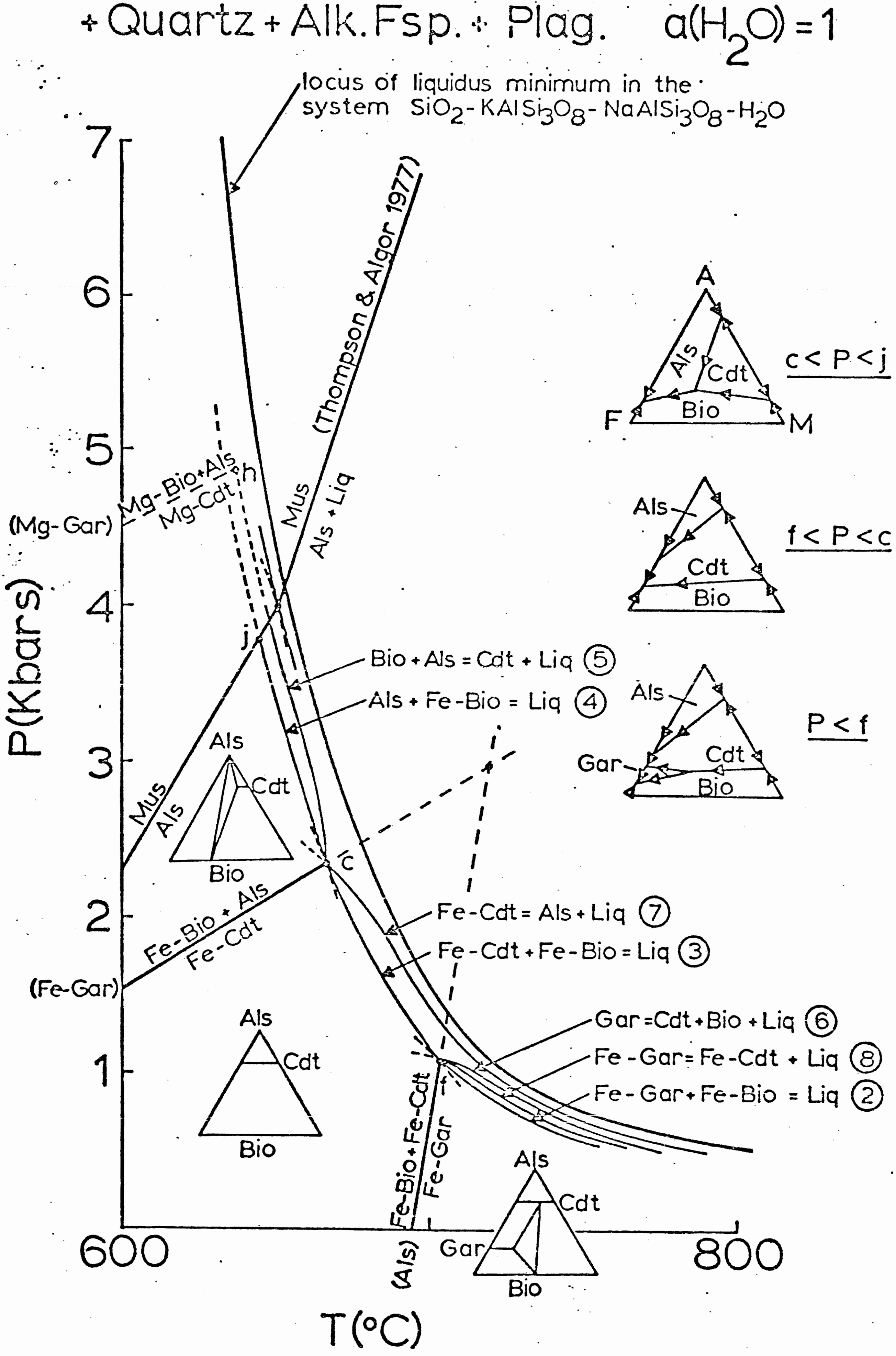

+ Quartz + Alk. Fsp. + Plag. a(H2O) = 1
locus of liquidus minimum in the system SiO2-KAlSi3O8-NaAlSi3O8-H2O
(Thompson & Algor 1977)
Mus
Als + Liq
P(Kbars)
7
6
5
4
3
2
1
600
800
T(°C)
(Mg-Gar)
Mg-Bio+Als
Mg-Cdt
h
j
c
f
Mus
Als
Fe-Bio + Als
Fe-Cdt
(Fe-Gar)
Fe-Bio+Fe-Cdt
Fe-Gar
(Als)
Bio + Als = Cdt + Liq ⑤
Als + Fe-Bio = Liq ④
Fe-Cdt = Als + Liq ⑦
Fe-Cdt + Fe-Bio = Liq ③
Gar = Cdt + Bio + Liq ⑥
Fe-Gar = Fe-Cdt + Liq ⑧
Fe-Gar + Fe-Bio = Liq ②
A
F
M
Als
Cdt
Bio
c < P < j
Als
Cdt
Bio
f < P < c
Als
Gar
Cdt
Bio
P < f
Als
Cdt
Bio
Als
Cdt
Bio
Als
Cdt
Gar
Bio

Fig. 8

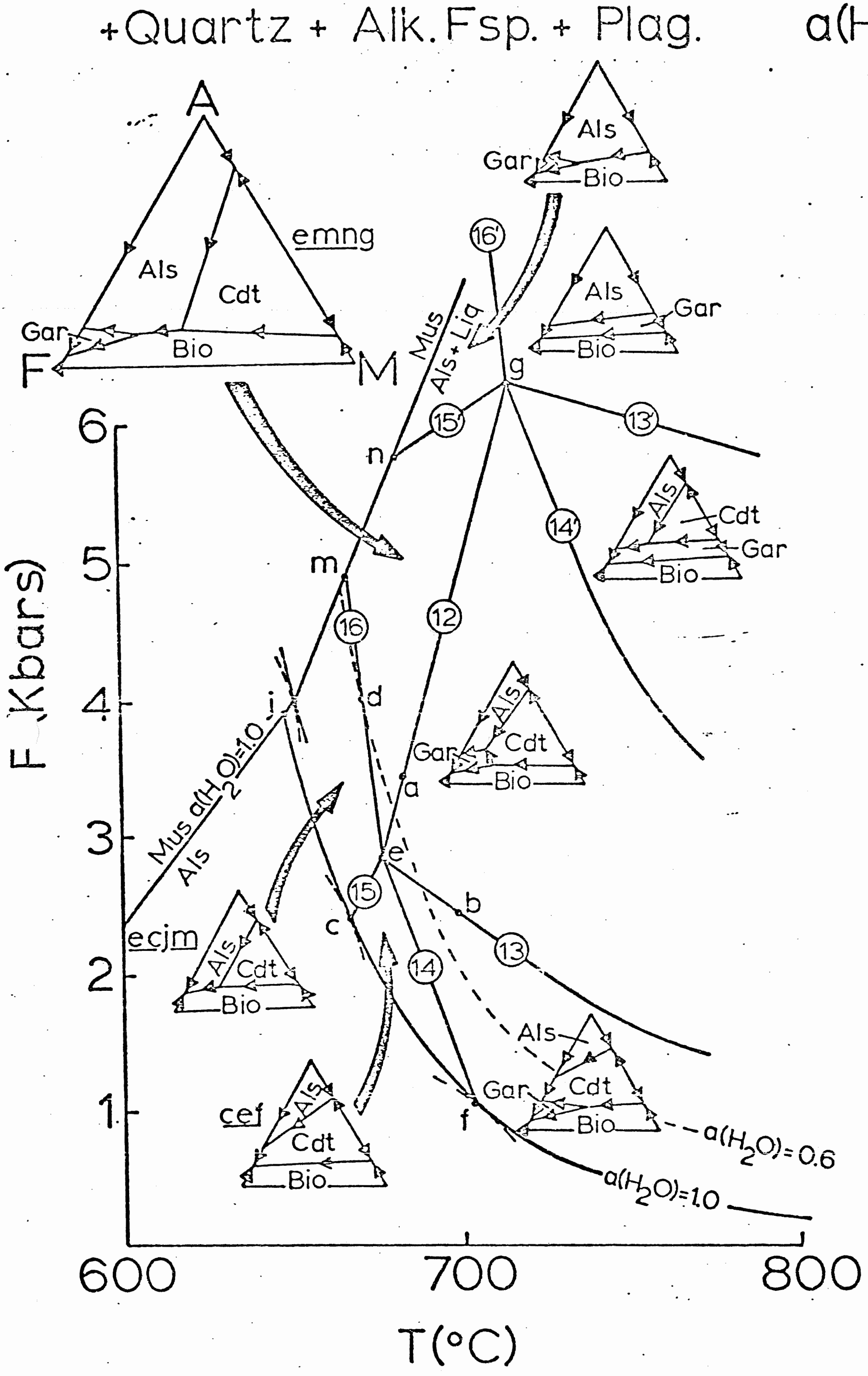

+Quartz + Alk.Fsp. + Plag.
a(H2O)≤1
A
F
M
Als
Cdt
Gar
Bio
emng
ecjm
cef
Mus
Als + Liq
Mus a(H2O)=1.0
Als
16'
15'
13'
14'
16
12
15
14
13
g
n
m
j
d
a
e
b
c
f
Als
a(H2O)=0.6
a(H2O)=1.0
P (Kbars)
1
2
3
4
5
6
600
700
800
T(°C)

Fig. 9

## 2.3 Chemical Considerations

Generally, Green (1977), Leake (1968), Birch and Gleadow (1974), and others have found garnets in equilibrium or equilibrating with silicic liquids to be almandine-rich (60-70%) with subordinate spessartine ($>10\%$) and pyrope ($<8\%$), and minor grossular (1-3%).

Stoddard and Miller (in press) have concluded from a compilation of 155 different garnet analyses from acid rocks, that an overwhelming majority of all garnets in granitic rocks have greater than 10% spessartine. They intrepreted this as the ability of manganese to stabilize garnet to conditions of granite crystallization. However, since many magmas are not rich in manganese, garnet can be expected to be an uncommon mineral (Stoddard and Miller, in press).

The existence of compositionally-zoned garnet crystals is a feature which means disequilibrium crystallization. In metamorphic rocks normal zoning of garnet is a Mn-Ca rich core surrounded by a Mg-Fe rich rim (Atherton, 1968; Chinner, 1962; Engel and Engel, 1960; Kretz, 1973), while the opposite sequence (Fe-Mg core and Mn-Ca rim) is termed reverse zoning (Green and Ringwood, 1968; Birch and Gleadow, 1974; Kurat and Scharbet, 1972). Atherton (1968), Kretz (1973) and others attribute normal zoning to progressive metamorphism, and Green (1977) concludes that it is strictly a metamorphic effect and cannot be applied to a garnet forming directly from a magma. Reverse or mixed zoning is explained in terms of ~~m~~non-equilibrium crystallization by resorption, retrograde metamorphism or ?. under cooling conditions in a magma (Grant and Weiblen, 1971; Kurat and Scharbet, 1972; Birch and Gleadow, 1974). X unclear.

Leake (1968) states that zoning is related to changes in temperature, pressure, activity of water, compositional changes in co-existing minerals, and the appearance or disappearance of new minerals. The mechanics of zonation have been explained by purely diffusional models (Anderson and Buckley, 1973) or by the Rayleigh fractionation effect (Hollister, 1966).

Leake (1968) explained normal zoning in granodiorite and aplite garnets as a feature of the growth mechanisms controlled by the diffusion of ions to the garnet nucleus, wherein the volume surrounding each garnet is rapidly depleted in relatively scarce elements (Mn) which are preferentially incorporated into the growing garnet. Mn in the garnet crystal decreases outward as it becomes exhausted from the liquid. This is the general principle behind the Rayleigh fractionation effect (Hollister, 1966).

Green and Ringwood (1968) observed reverse zoning of garnets in calc-alkaline plutonic and volcanic rocks. They concluded, as did Birch and Gleadow (1974), and Kurat and Schabet (1972), that reverse zoning represented equilibration of successive garnet layers with a normal increase of Mn and Fe in the liquid during crystallization. Green (1977) and Hsu (1968) modified this somewhat by showing that garnets crystallizing with decreased temperature (or increasing $FO_2$) preferentially incorporated Mn. This principle was used by Stoddard and Miller (in press), and Vennum and Meyer (1979) to explain their occurrences of reversely zoned garnets.

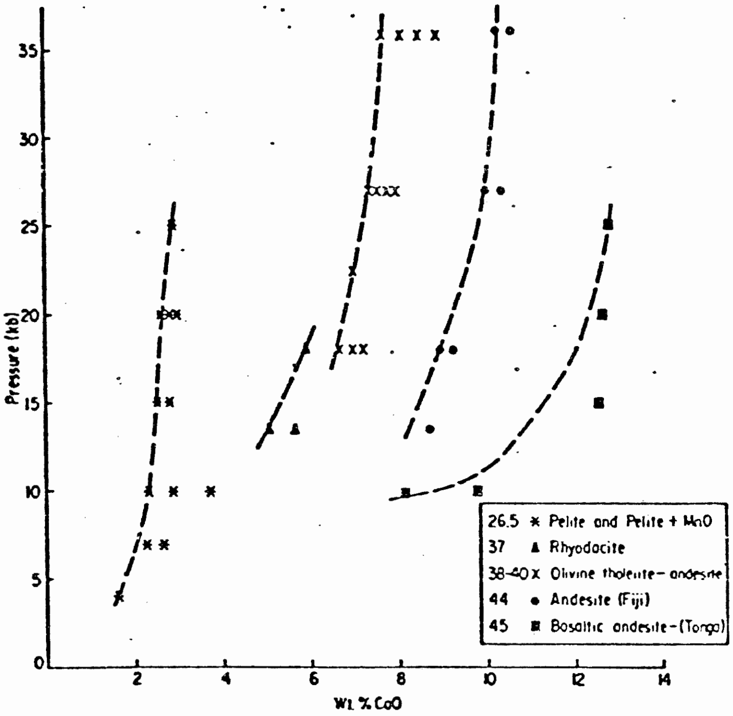
Birch and Gleadow (1974), on the other hand, suggest normal zoning could occur in a cooling magma if abundant Fe-Mn rich biotite began to crystallize simultaneously with garnet.

## 2.4 Origin

It must be kept in mind that the appearance of garnet is principally controlled by the bulk composition of a magma. This fact has permitted many authors to delineate specific origins of garnet based on composition alone (Hsu, 1968 and Green, 1977).

Green (1977) suggested that weight percent CaO was a key indicator of the source material and the pressure of crystallization (Fig. 10).

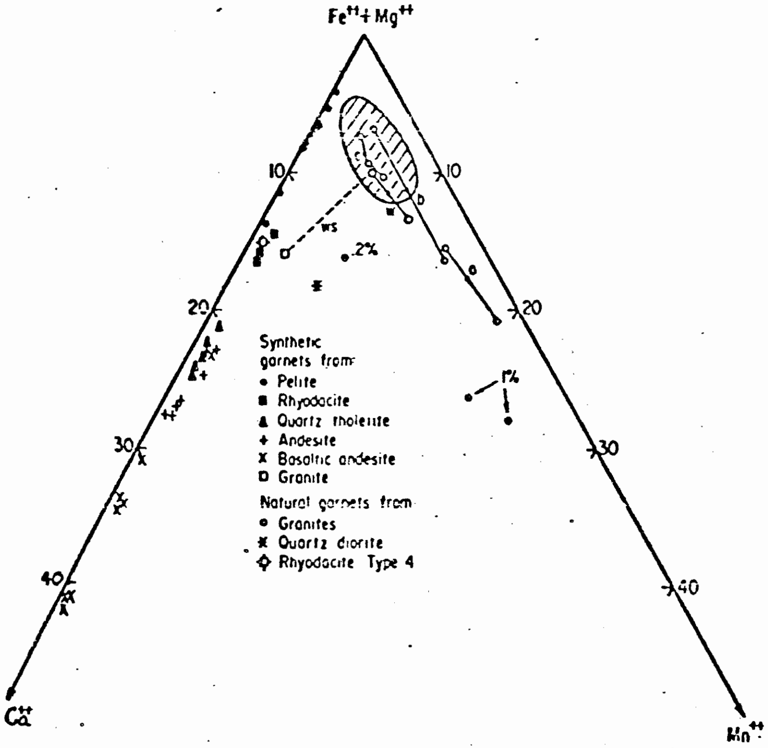
source of magma or host for garnet ?



Weight % CaO as Indicator of Source Material

Fig. 10

He further supplemented this with a triangular plot of Ca$^{++}$, Mn$^{++}$ and (Fe$^{++}$ + Mn$^{++}$), which was designed to classify garnets according to host rock (Fig. 11). Earlier work by Green (1976) indicated that pelitic sediments could produce an ademellite liquid at ~~of~~ pressures of 10 Kilobars and 780-820°C temperature. From this pelitic melt, garnet and cordierite crystallized at specific temperature and pressure ranges: garnet at 7-10 Kilobars, and less than 780-1,000°C; cordierite in the range at greater than 4-7 Kilobars and less than 780-1,000°C, ~~temperature.~~ This illustrated that garnet was an index mineral for pressures ≥ 7 Kilobars (25Km.) and



Triangular plot of atomic proportions of Ca, Mn, Mg+Fe for synthetic near-liquidus garnets obtained from a wide range of bulk compositions, and for a number of natural garnets in silicic igneous rocks from this work and from the literature. The pressure ranges over which the synthetic garnets crystallized from the respective compositions are as follows: Pelite: 7–25 kb; Pelite with added MnO (points marked 0.2% and 1% in the diagram): 4–6 kb; Rhyodacite: 10–18 kb; Quartz tholeiite: 18–36 kb; Andesite: 13.5–36 kb; Basaltic andesite: 10–27 kb. Shaded field denotes composition of garnets most commonly found in silicic igneous rocks. Solid lines join core and rim composition for 3 analyzed garnets from granites and arrows show increased spessartine content towards the rim (*a*, *b* from 2 garnet-bearing granites, New England, N.S.W.; *c* from the Cowra Granodiorite, N.S.W.; *w* from a granite at Wilson's Promontory, Victoria). The dashed line *ws* joins the core composition of the garnet seeds to the analyzed synthetic garnets obtained from an experimental run on the Wilson's Promontory granite at 10 kb. The garnet in the quartz diorite is from British Columbia (Warren, 1970) and the rhyodacite type 4 garnet is from Victoria (Birch and Gleadow, 1974)

Fig. 11

that cordierite indexed pressures $\lesssim 7$ Kilobars. However, subsequent work on manganese enrichment in a pelitic melt showed the stability fields of garnet and cordierite could substantially overlap under the right conditions (Green, 1977).

Green and Ringwood (1968) and Green (1976) indicated that almandine garnets with subordinate pyrope, and minor spessartine and grossular, reflected garnet xenocrysts produced during generation of the magma ~~at~~ in the lower crust or upper mantle.

Henson and Green (1973) suggested that garnets with greater than 2% CaO in calc-alkaline plutonic rocks, are refractory phases which have survived the partial melting of a pelitic source area. Stoddard and Miller (in press), and Green (1977), also concluded that Mn-rich garnets represent the partial melting of pelitic sediments; the contamination of the magma with pelitic material; or the differentiation and crystallization of I-type granites at shallow depths.

The case Green and Ringwood (1968), Vennum and Meyer (1974), Birch and Gleadow (1974) and others have made for magma-derived garnets is:

do you mean criteria for recognition or case for their existence as true magmatic phases?)

i) euhedral in shape;

ii) free of inclusions;

iii) uniform composition over a large area of the rock unit;

iv) minor zoning, preferably reverse;

v) spessartine enrichment with later phases of differentiation.

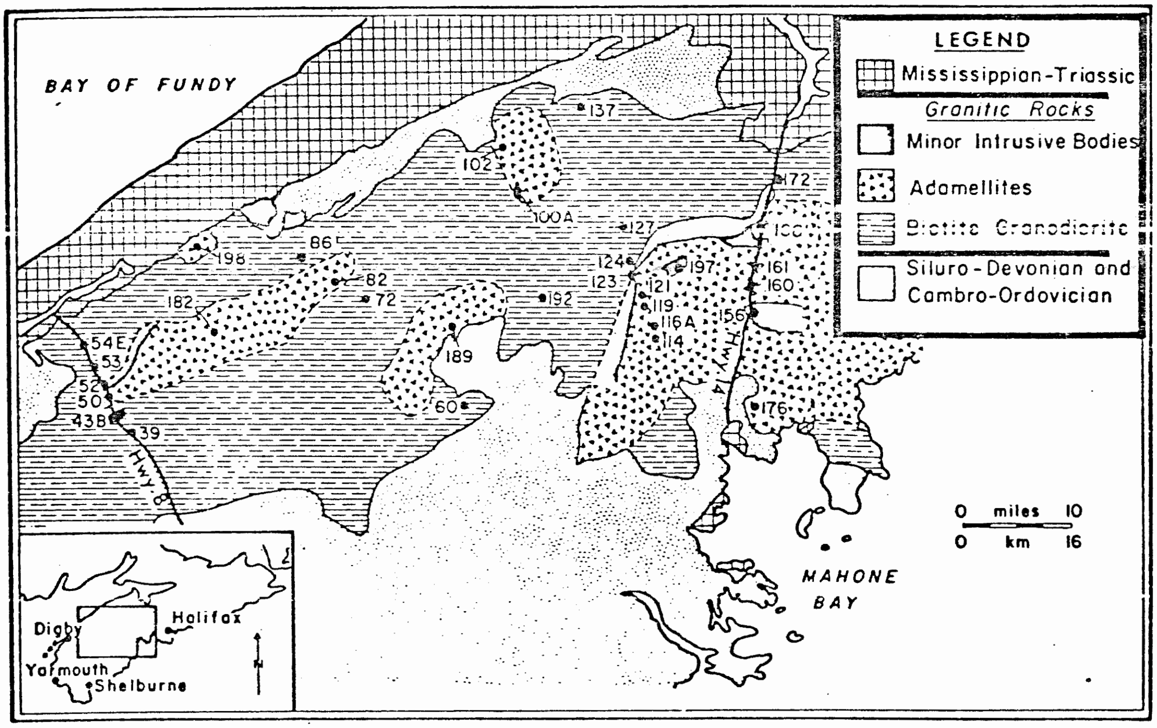
Finally, Bowen's (1937) concept of assimilation of sedimentary material can exert controls on the appearance or disappearance of garnet; garnet, cordierite, and sillimanite being intermediate steps in the assimilation process.

Good review of the literature

## Chapter 3 SOUTH MOUNTAIN BATHOLITH

### 3.1 Regional Geology

The South Mountain batholith underlies one-third of western Nova Scotia. It is a chemically-zoned, granodiorite/monzogranite/leucocratic monzogranite (minor intrusives) comagmatic suite which has intruded the meta-sediments of the Cambro-Ordovician Meguma Group (McKenzie and Clarke, 1975; Fig. 12).



Regional Geology of South Mountain Batholith

Fig. 12

derived from or formed in

The batholith is believed to have been derived in the lower crust by the hybridization of mantle and crustal melts during the Acadian orogeny, and emplaced as a single magma body (MacKenzie and Clarke, 1975). An outdated, see MJ Keen + others on a more recent model

average radiometric date of 371±7 m. y. (Reynolds, 1973) suggests the intrusion is Middle or Late Devonian in age. ~~Gravity and magnetic surveys (Garland, 1953) indicate the batholith is 55Km. in diameter and 17Km. deep, with the thickest part being in the New Ross area. It generally resembles a funnel-shaped cylinder. The contact with the Palaeozoic sediments is usually sharp and steeply dipping.~~

Meguma Group sediments which surround, or are enclosed~~,~~ by the intrusion have been metamorphosed to green~~-~~schist or amphibolite grade of regional metamorphism and the batholith has superimposed a hornblende-hornfels facies level of contact metamorphism.

The dominant lithology, biotite granodiorite, represents the first phase to have crystallized and is characteristically light grey to grey in color, co~~u~~arse-grained, hypidiomorphic granular in texture and contains feldspar phenocrysts. Locally, it may be non-porphyritic and medium grained. The groundmass is 29-40% quartz, 33-49% plagioclase, 9-23% K-feldspar, 8-15% biotite ~~and~~ with small amounts of accessory zircon, apatite and rarely garnet~~, occur~~.

Xenoliths of metasedimentary material are a common feature in the granodiorite. Most have recrystallized to an overall granitic texture with a mineralogy of granodiorite, except for the common occurrence of garnet. Xenoliths occur throughout the granodiorites, suggesting xenoliths in the centre are likely stoped from the roof of the pluton. what about marginal facies xenoliths Many of the large xenoliths are quite angular and still maintain sedimentary features.

Monzogranite makes up about 25% of the batholith. It intrudes the granodiorites in a number of irregularly shaped, independent bodies. They differ from granodiorites by the near absence of xenoliths and the appearance of muscovite and accessory andalusite. They have a similar mineralogical make-up of 31-45% quartz, 20-26% plagioclase, 23-40% K-feldspar, 3-10% biotite and 1-5% muscovite; accessory minerals ~~being~~ are apatite, zircon, andalusite and garnet.

Leucocratic monzogranite (aplite and porphyry) dykes are found cutting both the granodiorites and monzogranites. Typically they range from a few centimetres in size to a few metres in width, and are often associated with monzogranite bodies. Their contacts are sharp.

The aplite phase of the leucocratic monzogranite is medium to fine grained, equigranular in texture and whitish or pinkish grey in color. Their mineralogy is 30-40% quartz, 20-46% plagioclase, 11-36% K-feldspar, 1-5% biotite and 4-12% muscovite. Accessory minerals are apatite, zircon, andalusite, tourmaline, fluorite, garnet and topaz. However, not all the accessory minerals are found in a single dyke.

The petrology of the batholith indicates crystallization occurred at temperatures less than 850°C and 4 Kilobars pressure (McKenzie and Clarke, 1975).

The effect of differentiation on the bulk composition of each rock type is illustrated in Figure 13.

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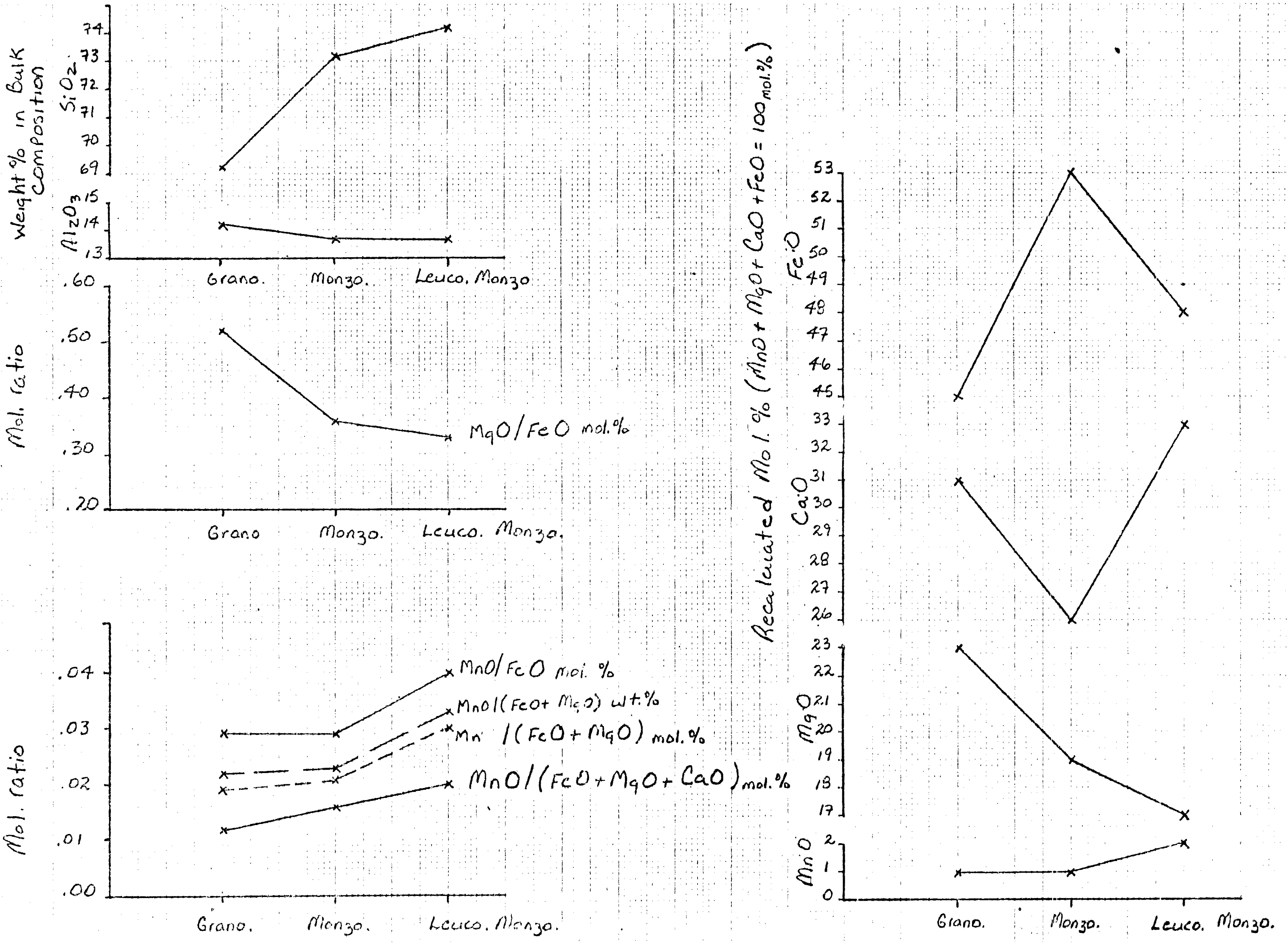

Fig.13 Effect of Differentiation on Composition of phases

## 3.2 Garnet Location and Petrography

Garnets for this study were collected from eight locations in the eastern half of the South Mountain batholith. Their locations are given in Fig. 14, and a brief description of garnet and its associated host rock is provided in Table 1.

The garnet-biotite textural relationships found are illustrated supplemented by sketches. The relationship in biotite granodiorite (localities: KL, MU, NG) is typified by a sketch of a Kearney Lake garnet - sample KL-1 (Fig. 15); those of AS and EC by sample AS-1 (Fig. 16). Biotite, in relation to the garnet crystals of $ED_m$, is found in three ways: biotite forming the core of a large garnet grain (Figs. 17, 18 and 19); partially subhedral ? euhedral grains with one side biotite (Figs. 20 and 21); and small ( Zmm) ? 2 mm ? subhedral-euhedral garnets which are not psuedomorphed by biotite, but are associated with it (Fig. 22). $ED_a$ and CH localities are characterized by Fig. 23. The textures are discussed in 5.1.

Fig.14

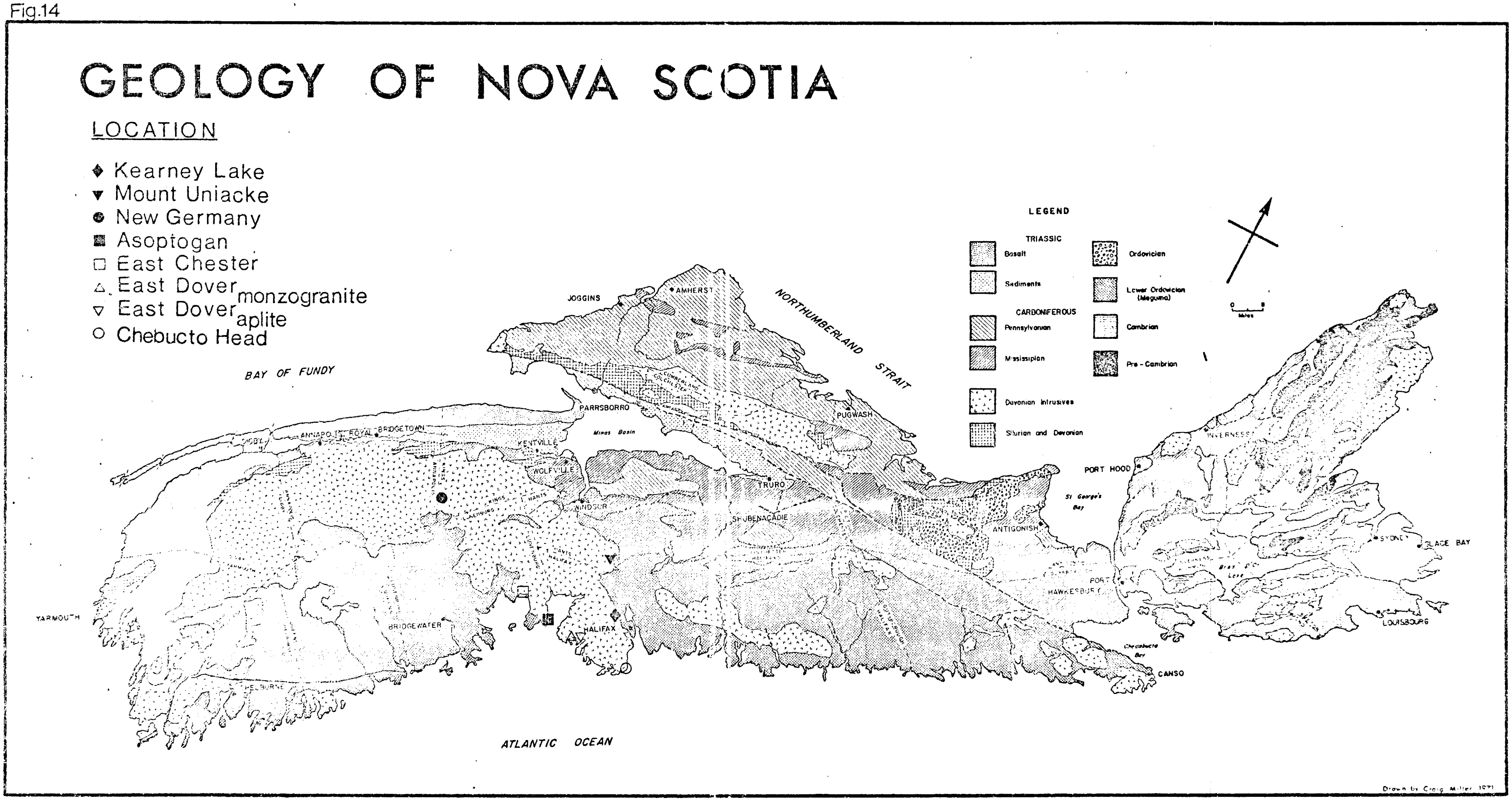
GEOLOGY OF NOVA SCOTIA
LOCATION
♦ Kearney Lake
▼ Mount Uniacke
● New Germany
■ Asoptogan
□ East Chester
△ East Dover monzogranite
▽ East Dover aplite
○ Chebucto Head
LEGEND
TRIASSIC
Basalt
Sediments
CARBONIFEROUS
Pennsylvanian
Mississipian
Devonian Intrusives
Silurian and Devonian
Ordovician
Lower Ordovician (Meguma)
Cambrian
Pre - Cambrian
Miles
BAY OF FUNDY
NORTHUMBERLAND STRAIT
ATLANTIC OCEAN
JOGGINS
AMHERST
PARRSBORRO
PUGWASH
Minas Basin
DIGBY
ANNAPOLIS ROYAL
BRIDGETOWN
KENTVILLE
WOLFVILLE
WINDSOR
TRURO
SHUBENACADIE
ANTIGONISH
PORT HOOD
St George's Bay
INVERNESS
SYDNEY
GLACE BAY
PORT HAWKESBURY
Bras d'Or Lake
LOUISBOURG
Chedabucto Bay
CANSO
HALIFAX
BRIDGEWATER
YARMOUTH
SHELBURNE
Drawn by Craig Miller 1971

Table 1 Location and Binocular Description of Garnet Samples

| Location | Abr. | Host Rock | Garnet | Garnet's Assoc. with Xenolith? | Approx. Distance From Contact |
|---|---|---|---|---|---|
| Windsor-Chester turnoff, HW 103, Chester County | EC | Road cut otc., cg. monzogranite, xenolith conc. 1% | Anhedral shape extensive biotite rim approx. 5-7mm. dia. deep red in color | Yes | 4.0 Kilometers (?) |
| .8Km east of Coleman Cove Rd. on HW 329, Chester County | AS | cg. leucocratic pulse in biotite granodiorite xenolith conc. 2% | anhedral shape, extensive biotite rim 7mm. dia., deep red in color | Yes | 1.5 Kilometers |
| Junction HW 333 and East Dover Rd., Halifax County | $ED_m$ | Med-coarse grained monzogranite xenolith conc. 0% | subhedral-euhedral shape, minor - no mantling by biotite approx. 2.5-5mm dia. | No | 1-2 Kilometers |
| Junction HW 333 and East Dover Rd., Halifax County | $ED_a$ | wh-lt.gry allotriomorphic granular leucocratic monzogranite xenolith conc. 0% | euhedral shape, 2mm. dia., no psuedomorphic biotite | No | 1-2 Kilometers |
| 250m. north of Duncan's Cove, Halifax County | CH | med. grained monzogranite | subhedral shape 2mm. dia., no psuedomorphic biotite | No | 1-2 Kilometers |
| 350m. west of the northern end of Washmill Lake, near Kearney Lake, Halifax County | KL | Massive otc. of cg. biotite-granodiorite with fd. pheno. xenolith conc. 2% | Subhedral-anhedral, approx. 3.5-7mm. dia. extensively mantled by biotite deep red in color | Yes | 200 meters |
| 2.5Km. west of Mt. Uniacke turnoff, on HW 101, Hants County | $MU_1$ | Road cut otc. cg. biotite-granodiorite with fd. pheno. xenolith conc. 10% | Sub-anhedral shape approx. 5-8mm dia. extensively mantled by biotite deep red in color | Yes | 2.5 Kilometers |

Table 1 (cont'd)

| Location | Abr. | Host Rock | Garnet | Garnet's Assoc. with Xenolith? | Approx. Distance From Contact |
|---|---|---|---|---|---|
| 3.0Km. west of Mt. Uniacke turnoff, on HW 101, Hants County | $MU_2$ | Road cut otc. cg. biotite-granodiorite with fd. pheno. xenolith conc. 5% | sub-anhedral shape, approx. 5-8mm dia. extensive biotite rim, deep red in colour | No | 7.0 Kilometers |
| On Upper Sixty Lakes Rd. between East Dalhousie and Greenwood, King's County.<br>1) South end of West Twin Lake<br>2) Sough end of East Twin Lake | NG | Road cut otc., mg. non por. granodiorite xenolith conc. 1% | anhedral shape approx. 7-25mm dia., extensive biotite rim, deep red in color | No | 7.8 Kilometers |

Sample KL 1
Thin section

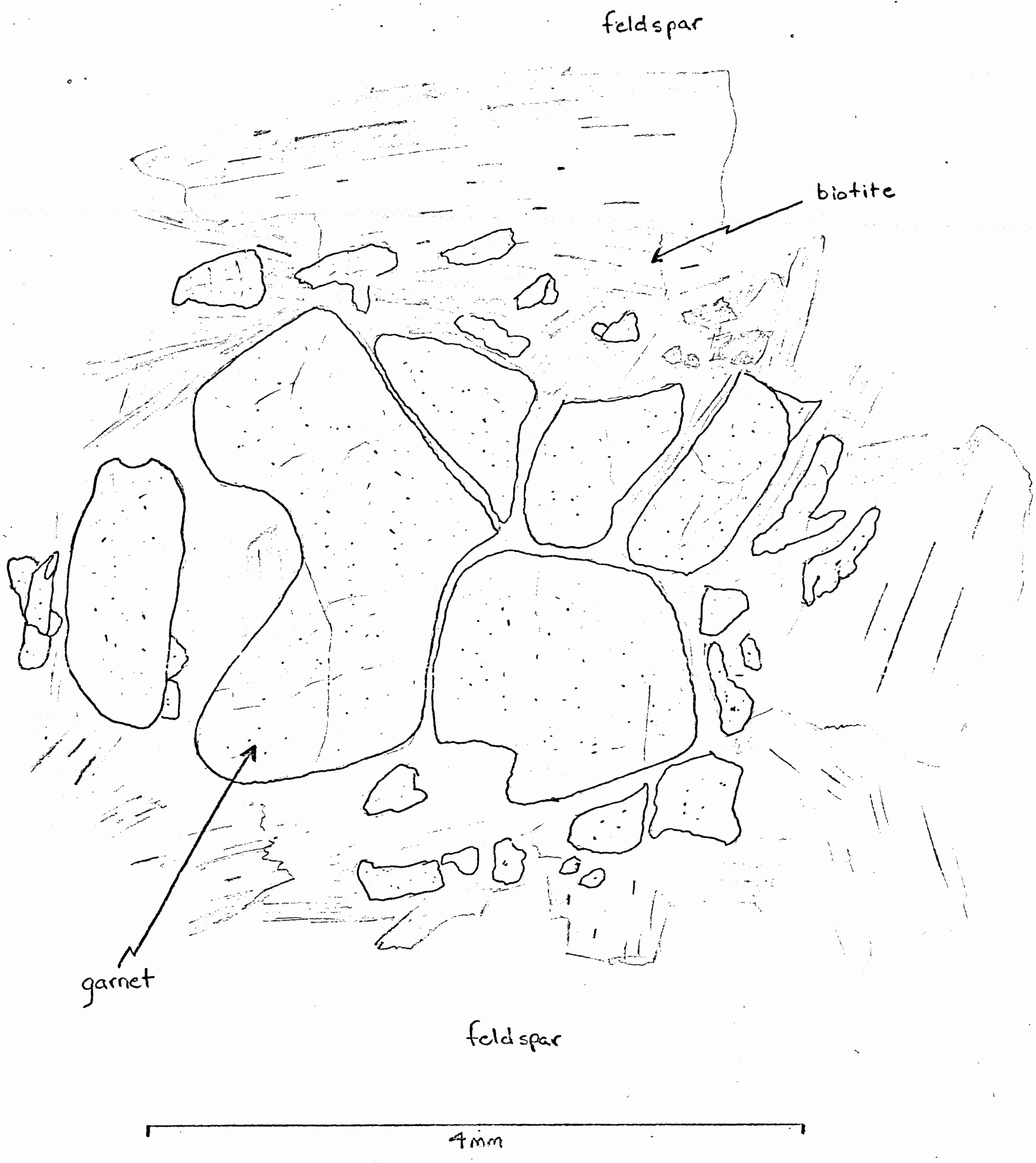

Fig.15 Garnet with a Reaction Rim of Biotite

Sample AS 1

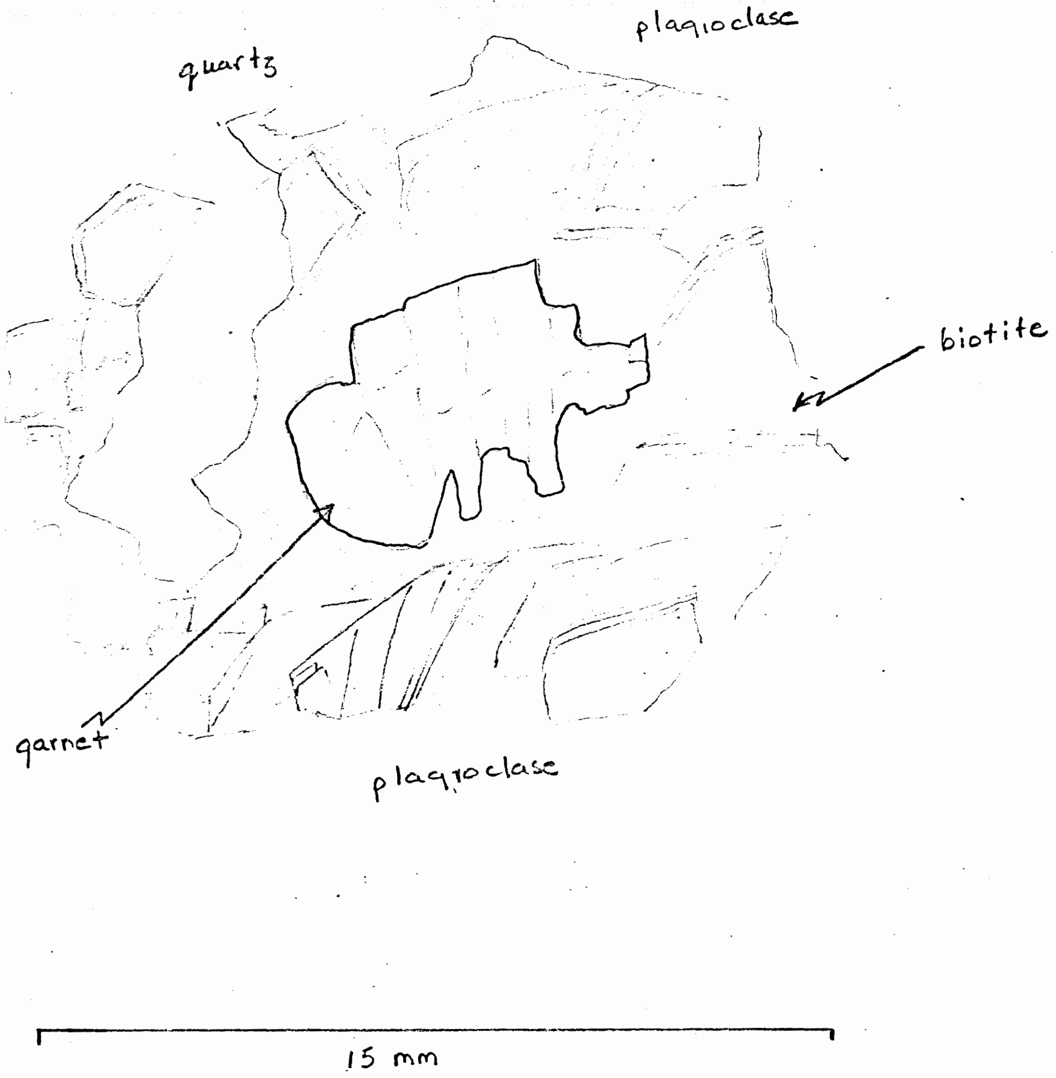

Fig.16 Garnet with a Reaction Rim of Biotite

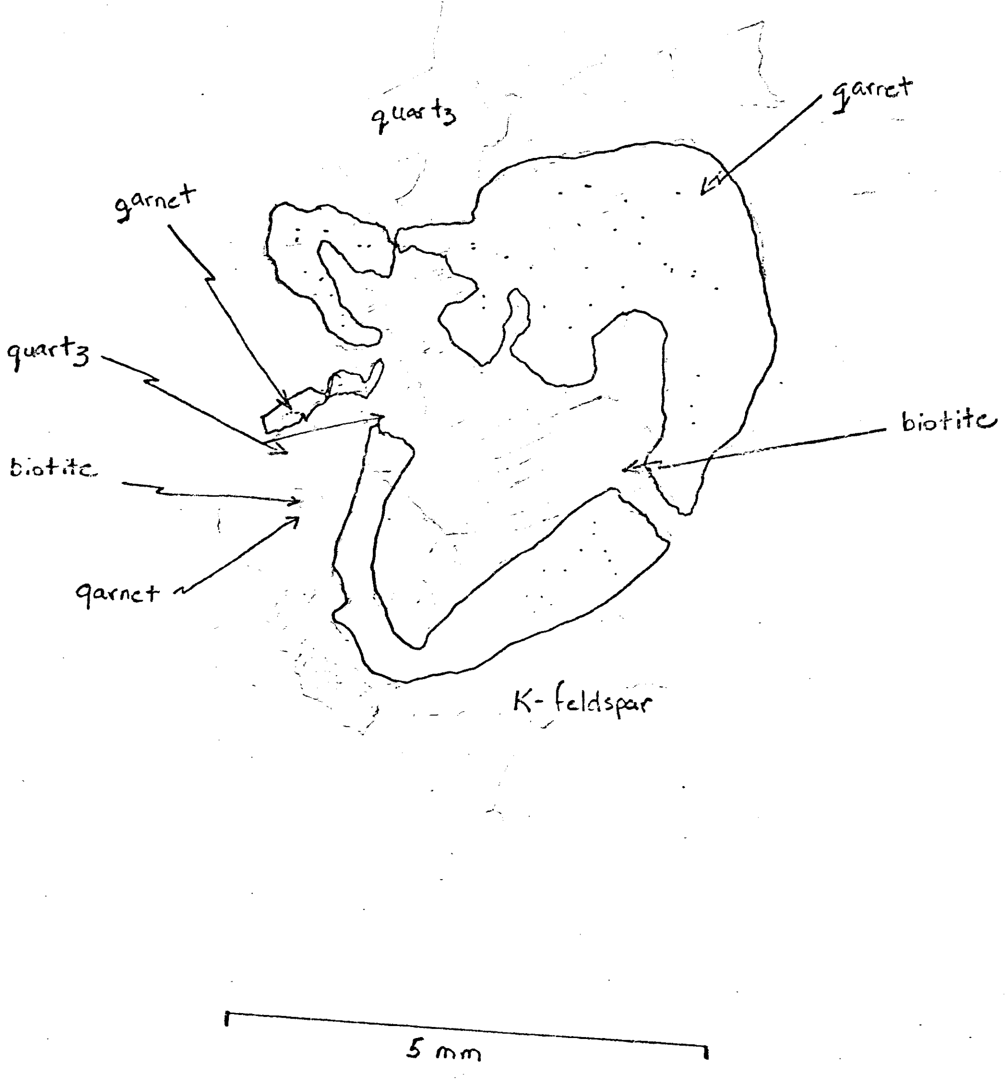

Fig. 17 Subhedral Garnet with a Biotite Core

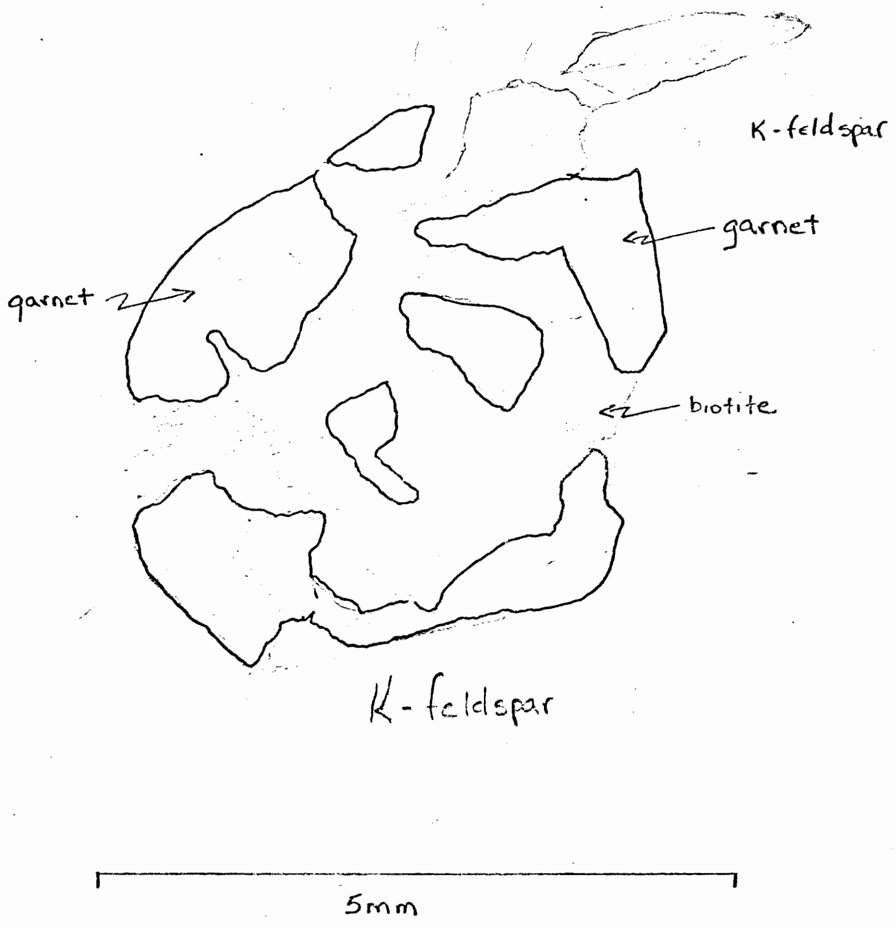

Fig. 18 Subhedral Garnet with a Biotite Core

P.C. 4

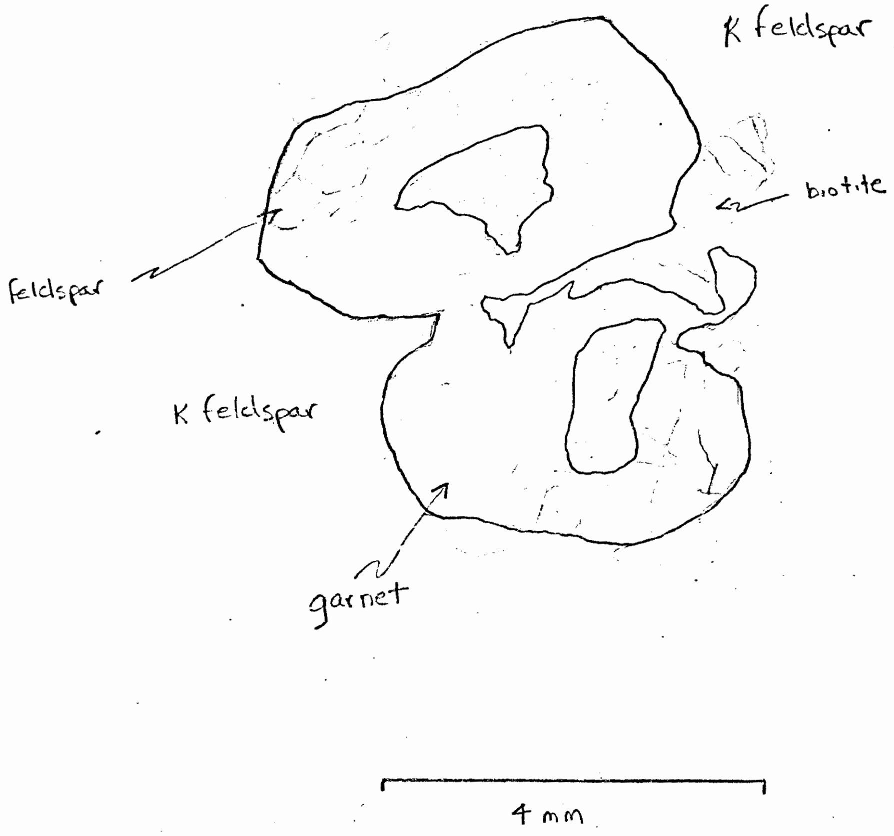

Fig. 19 Euhedral Garnet with a Biotite Core

PC5

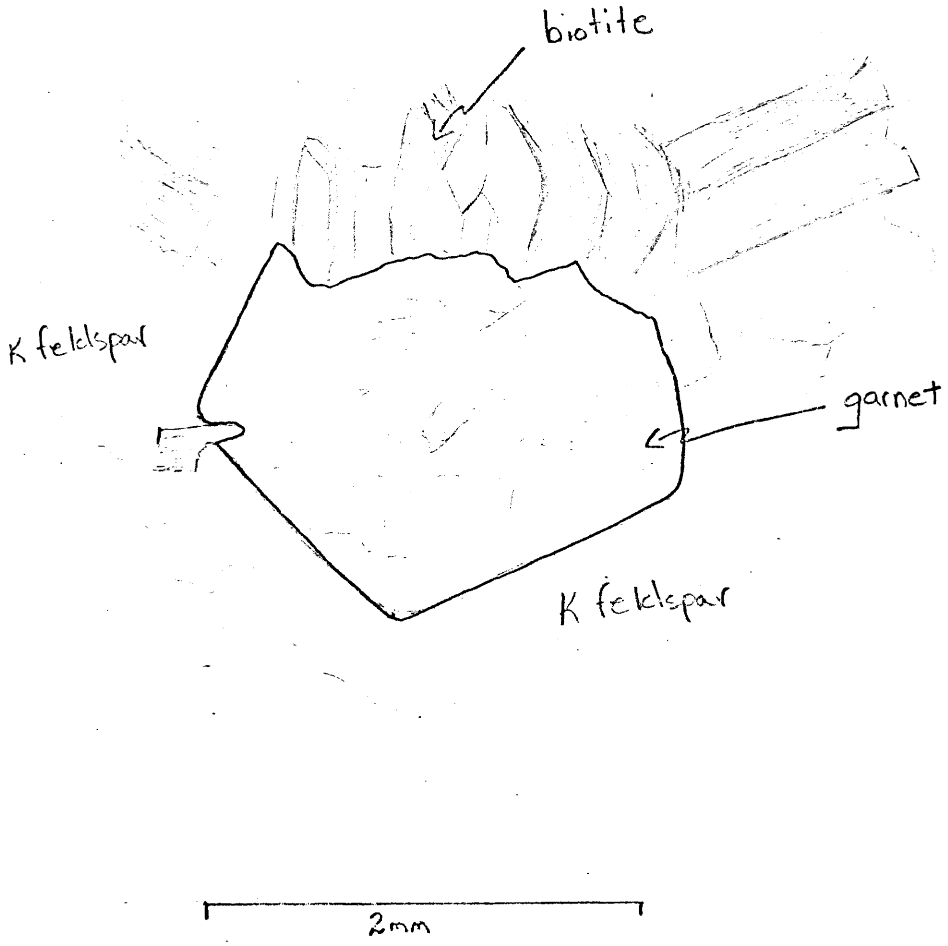

Fig. 20    Subhedral Garnet with a Biotite Edge

PC 7

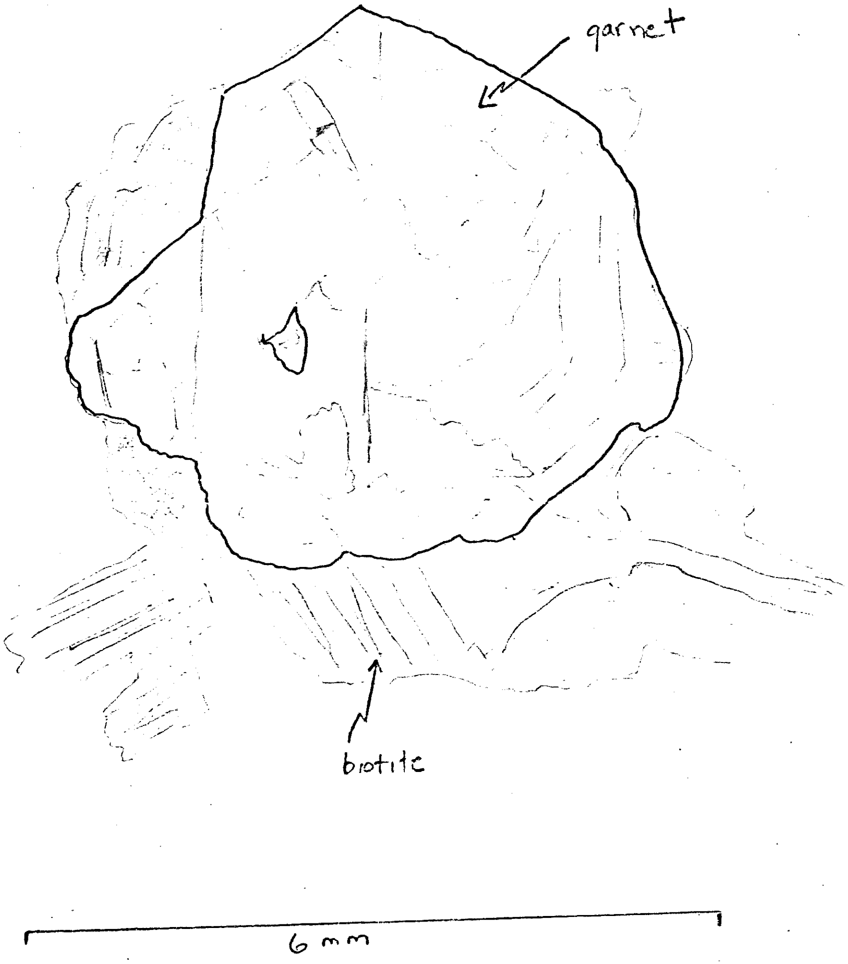

Fig. 21 Subhedral Garnet with a Biotite Edge

PC6

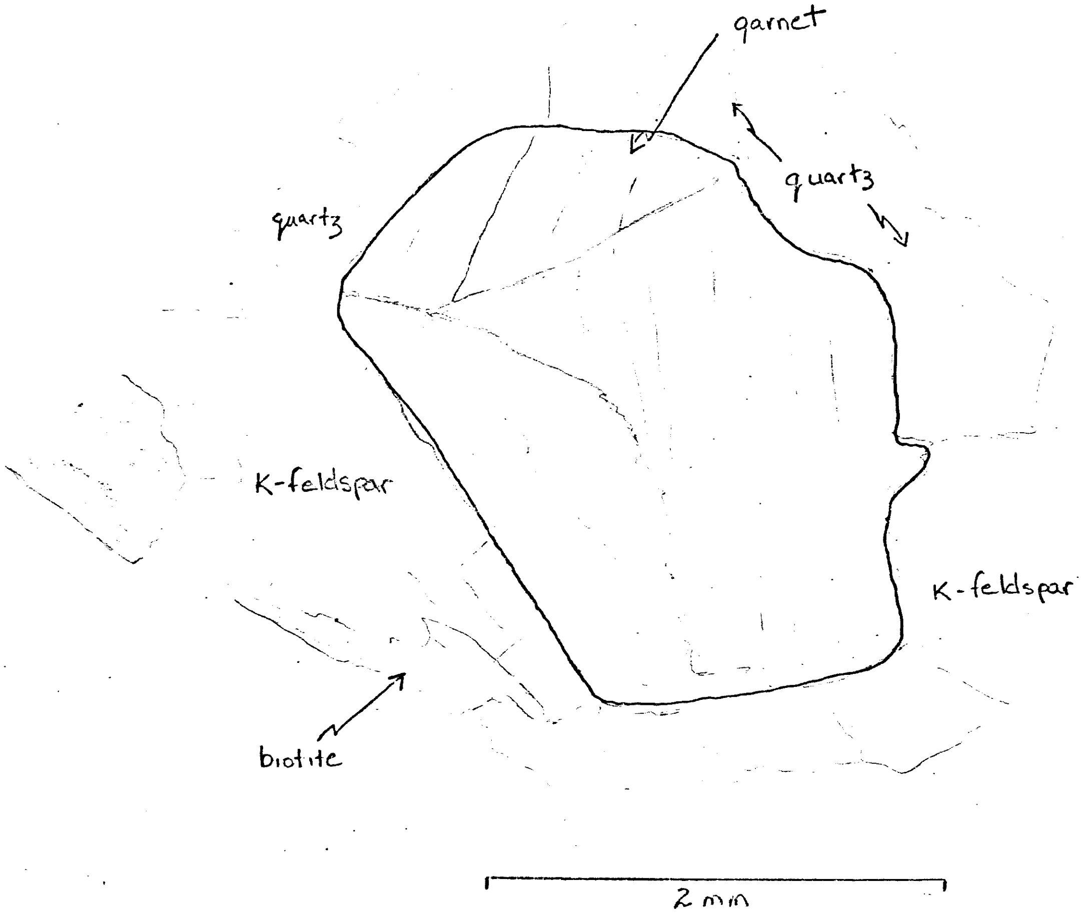

Fig. 22 Euhedral Garnet

AS-1

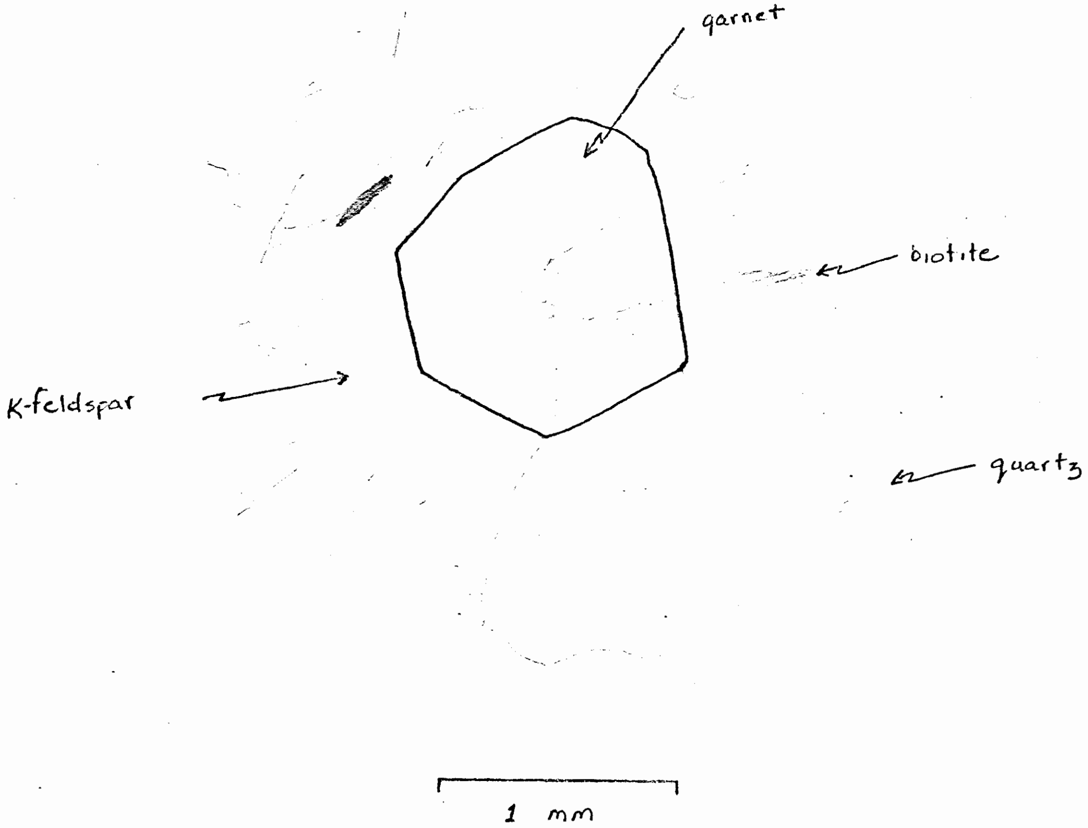

Fig. 23 Euhedral Garnet

# Chapter 4 GARNET ANALYSIS

## 4.1 Data

Chemical data used in this thesis were compiled by performing over 250 microprob~~l~~e analyses on 50 pairs of co-existing garnet and biotite. An average composition for each locality is provided in Table 2.

## 4.2 Chemical Classification

Garnets in the South Mountain batholith are almandine-ri~~g~~ch (67-78%) with subordinate amounts of pyrope (10-23%) or spessartine (3-15%), and a relatively constant minor amount of grossular (3-4%).

The percentage of each garnet end member for every location is provided in Table 3.

## 4.3 Chemical Variations

Except for CaO and $K_2O$, which are relatively constant in all samples, the variation in average composition of biotite and garnet ? between in each? localities is presented in Fig. 24. Generally, MgO is lower in the East Dover samples (EDm and EDa) but enriched in the biotites from Mount

## Table 2 Average Analyses

| | NG | KL | MU | $ED_m$ | $ED_a$ | EC | AS | CH |
|---|---|---|---|---|---|---|---|---|
| **Garnet** | | | | | | | | |
| $SiO_2$ | 36.15±.51 | 36.34±.55 | 37.21±.33 | 36.03±.69 | 35.63±.20 | 36.60±.23 | 36.75±.26 | 36.29±.05 |
| $Al_2O_3$ | 20.65±.25 | 20.87±.10 | 21.48±.05 | 20.33±.25 | 20.26±.13 | 20.75±.17 | 20.72±.19 | 21.21±.03 |
| FeO | 33.97±.78 | 33.50±.41 | 31.13±.87 | 33.12±.56 | 32.85±.50 | 35.59±.97 | 33.05±.50 | 33.71±.24 |
| MnO | 2.24±.91 | 4.58±1.24 | 2.68±1.75 | 6.27±1.72 | 6.91±2.21 | 1.55±.67 | 4.62±.95 | 2.74±.40 |
| MgO | 4.43±.46 | 3.64±.55 | 5.97±1.09 | 2.63±.69 | 2.60±.71 | 4.01±.78 | 3.94±.55 | 3.52±.21 |
| CaO | 1.05±.17 | 1.12±.09 | 1.40±.16 | 1.02±.28 | 0.93±.18 | 1.18±.19 | 1.29±.25 | 1.22±.07 |
| $Na_2O$ | 0.08±.09 | 0.04±.06 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| TOTAL: | 98.53 | 100.24 | 100.02 | 99.50 | 99.17 | 99.88 | 100.50 | 98.69 |
| **Biotite** | | | | | | | | |
| $SiO_2$ | 37.46±.93 | 33.63±.12 | 35.06±.45 | 35.73±1.68 | 34.72 | 34.95±.57 | 33.55±1.45 | |
| $TiO_2$ | 2.33±.42 | 2.56±.50 | 2.63±.50 | 3.33±.80 | 4.56 | 2.86±.55 | 2.45±.54 | |
| $Al_2O_3$ | 20.45±.97 | 20.00±.16 | 18.64±.67 | 20.04±.77 | 19.65 | 20.34±.58 | 19.88±.20 | |
| FeO | 20.93±.65 | 21.69±.10 | 24.49±.76 | 26.39±1.99 | 27.16 | 24.49±.73 | 26.13±1.6 | |
| MnO | 0.20±.09 | 0.38±.01 | 0.27±.07 | 0.50±.15 | 0.35 | 0.27±.09 | 0.50±.20 | |
| MgO | 6.95±.76 | 7.75±.10 | 7.18±.83 | 3.86±.26 | 3.75 | 6.42±.02 | 6.85±.03 | |
| $Na_2O$ | 0.03±.05 | 0.13±.01 | 0.00 | 0.12±.08 | 0.17 | 0.03±.13 | 0.12±.02 | |
| $K_2O$ | 8.95±1.26 | 9.22±.66 | 9.25±.25 | 9.51±.13 | 9.48 | 9.29±.14 | 8.12±1.51 | |
| TOTAL: | 97.50 | 95.57 | 97.72 | 99.66 | 99.84 | 98.78 | 97.60 | |

Garnet:
NG avg. 16 analyses
KL avg. 6 analyses
MU avg. 33 analyses
$ED_m$ avg. 20 analyses
$ED_a$ avg. 4 analyses
EC avg. 6 analyses
AS avg. 5 analyses
CH avg. 2 analyses

Biotite:
NG avg. 10 analyses
KL avg. 3 analyses
MU avg. 10 analyses
$ED_m$ avg. 9 analyses
$ED_a$ avg. 2 analyses
EC avg. 3 analyses
AS avg. 3 analyses

Table 3 End Member Percentages of Garnets at Each Locality

| | MU | KL | NG | $ED_m$ | $ED_a$ | AS | EC | CH |
|---|---|---|---|---|---|---|---|---|
| almandine | 67 | 73 | 75 | 73 | 72 | 71 | 78 | 76 |
| pyrope | 23 | 14 | 17 | 10 | 10 | 15 | 16 | 14 |
| spessartine | 6 | 10 | 5 | 14 | 15 | 10 | 3 | 7 |
| grossular | 4 | 3 | 3 | 3 | 3 | 4 | 4 | 3 |

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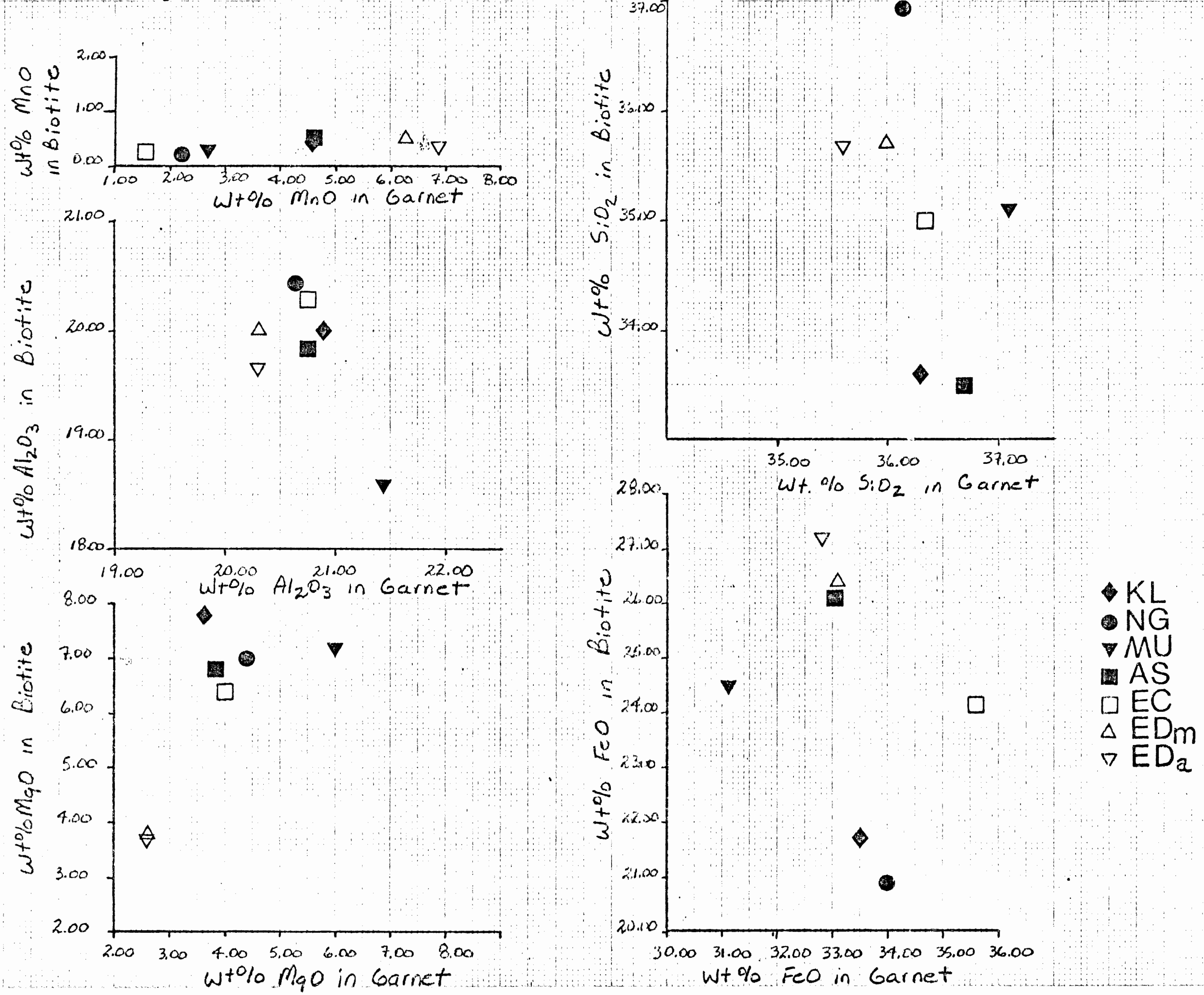
Fig. 24 Chemical Variation of Biotite and Garnet



Uniacke. $Al_2O_3$ is consistent in all samples except Mount Uniacke biotites which are depleted decreased in $Al_2O_3$. MnO content is variable in garnets but relatively constant in biotites, with East Dover garnets having the highest MnO. $SiO_2$ and FeO content is somewhat stable in garnet and more variable in biotite. However, the change in $SiO_2$ is more subtle than the change in FeO.

Since the CaO content in garnets is nearly constant, a ternary plot of FeO, MgO and MnO mol. percents helps to illustrate the compositional differences amongst localities. The plot shows a uniform trend in composition which is convex towards FeO, with MnO-rich East Dover samples forming one end and Mount Uniacke MgO-rich garnets forming the other (Fig. 25). This is more clearly delineated by plotting core and rim analyses (Fig. 26).

## 4.4 Compositional Zoning

Chemical profiles across garnet crystals reveal compositional zoning with respect to FeO, MgO and MnO. New Germany and Kearney Lake garnets are normally zoned (Fig. 27) and garnets from East Dover are reversely zoned (Fig. 28). To help demonstrate how the compositions of samples change, FeO, MgO and CaO are plotted against the most strongly zoned element, MnO (Fig. 29, 30, 31 and 32).

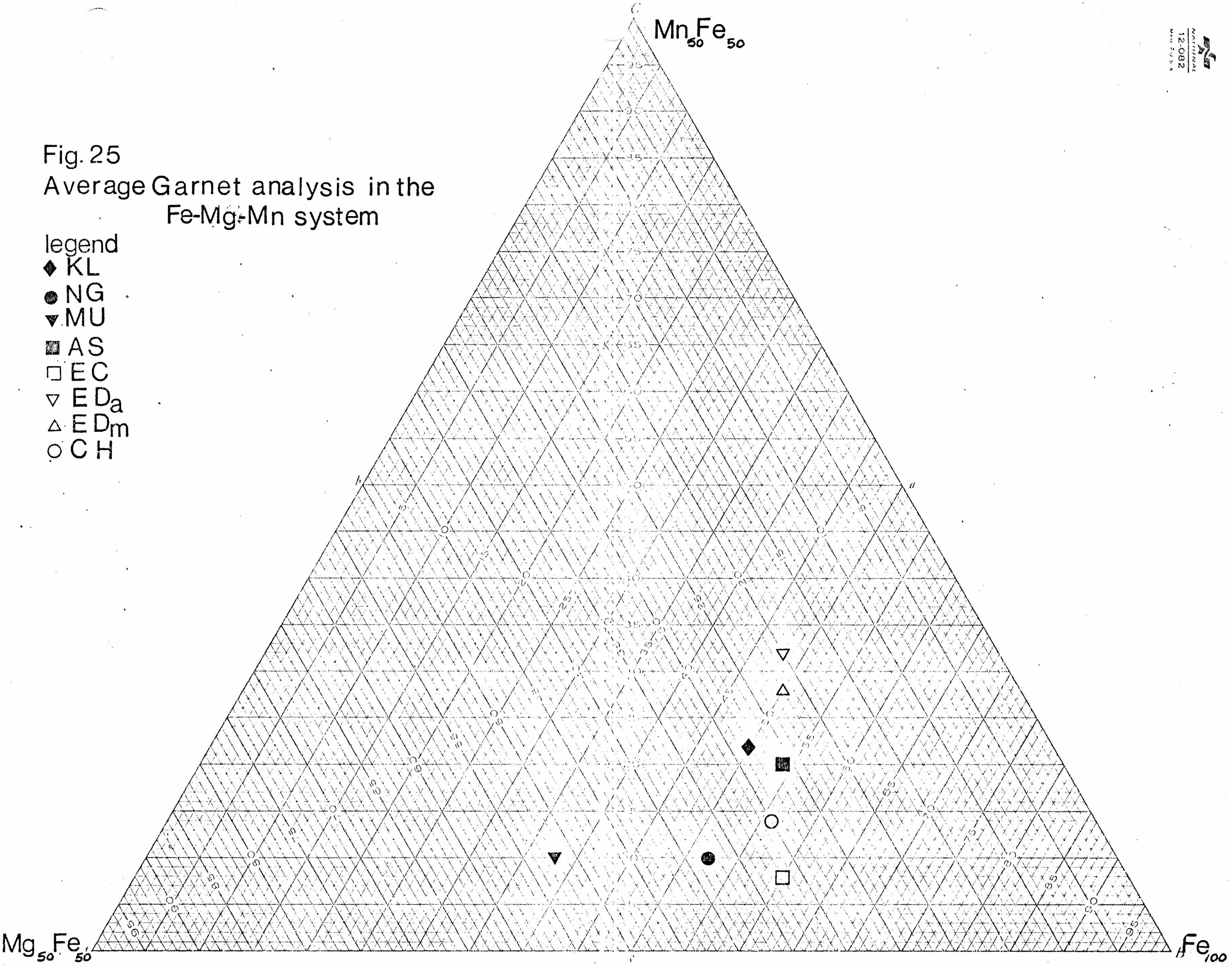
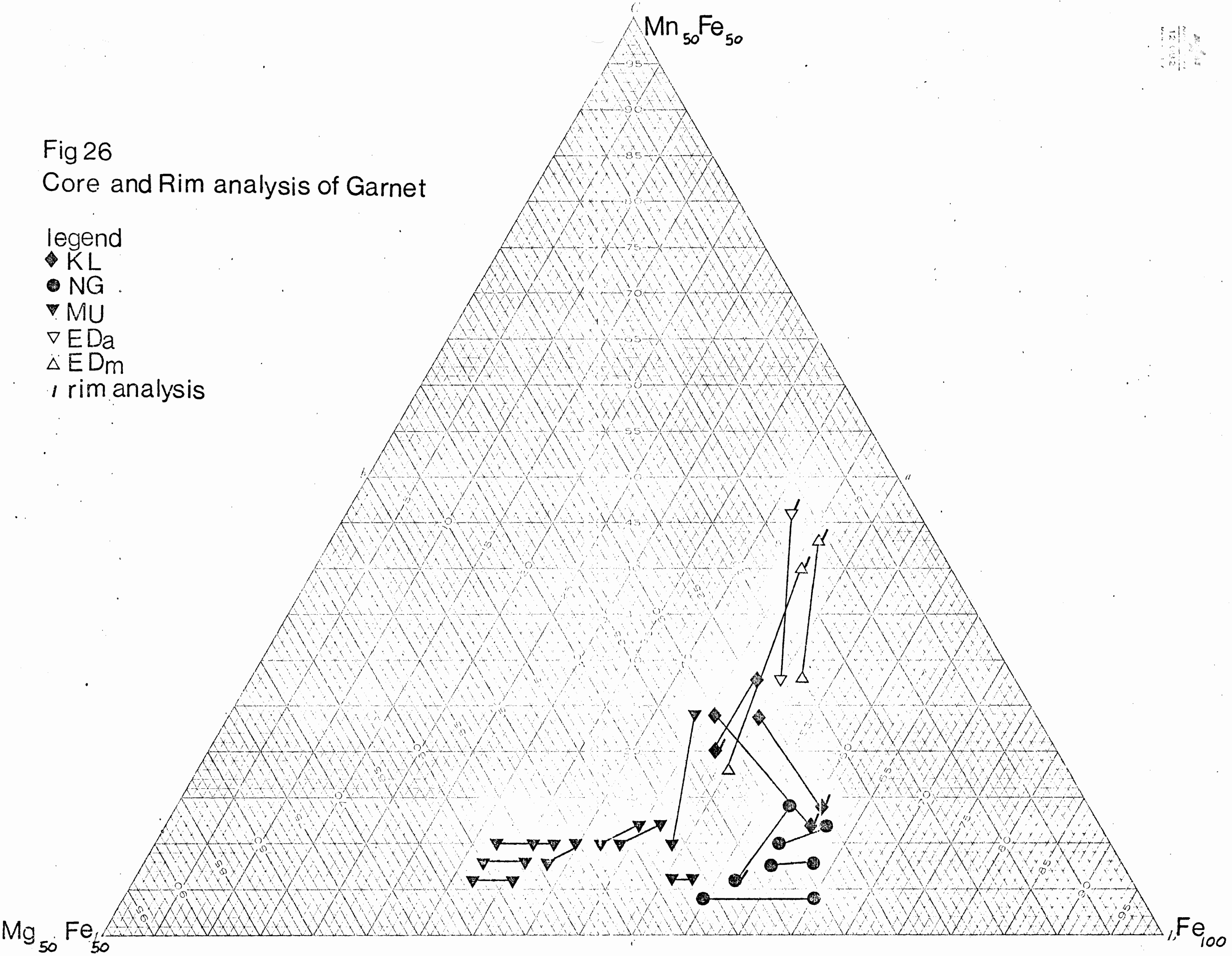


Fig. 25
Average Garnet analysis in the Fe-Mg-Mn system

Triangular Co-ordinate

# Fig 26
Core and Rim analysis of Garnet



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# Fig. 27 & 28 Composition Profiles of Garnet

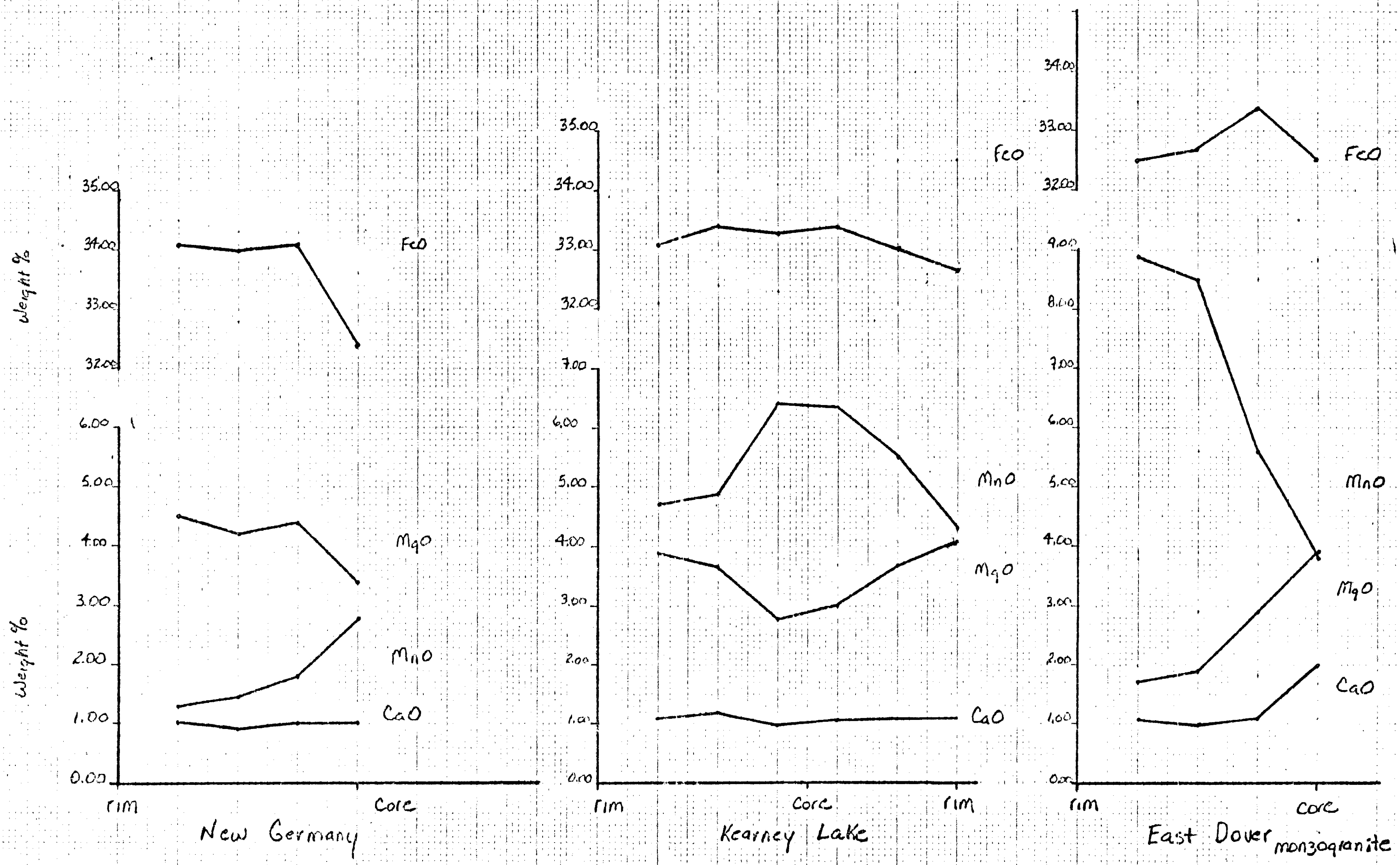

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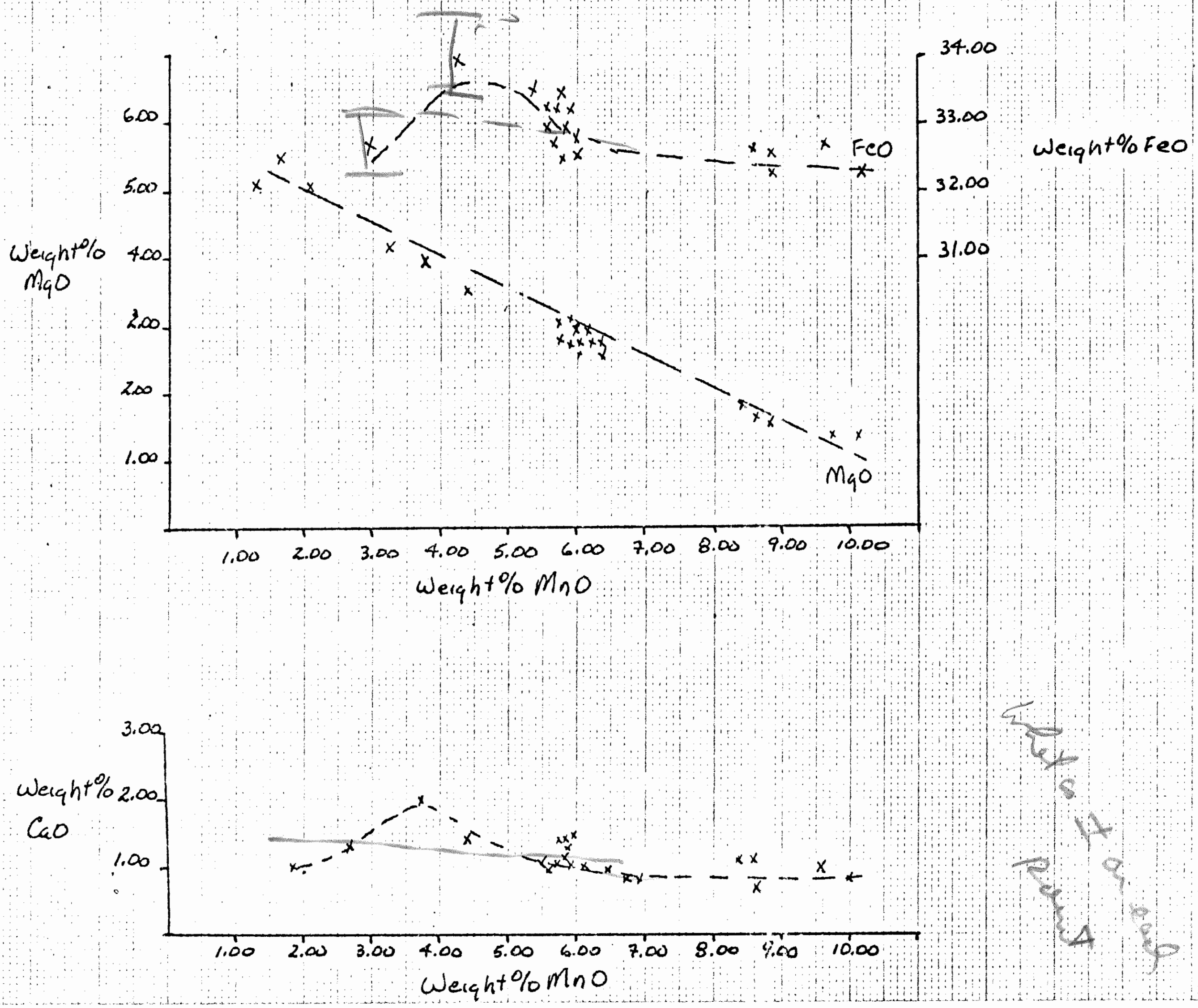
Fig. 29 East Dover garnet analyses



What's the end
Result

METRIC

Fig. 30 Garnet analyses of New Germany and Kearney Lake

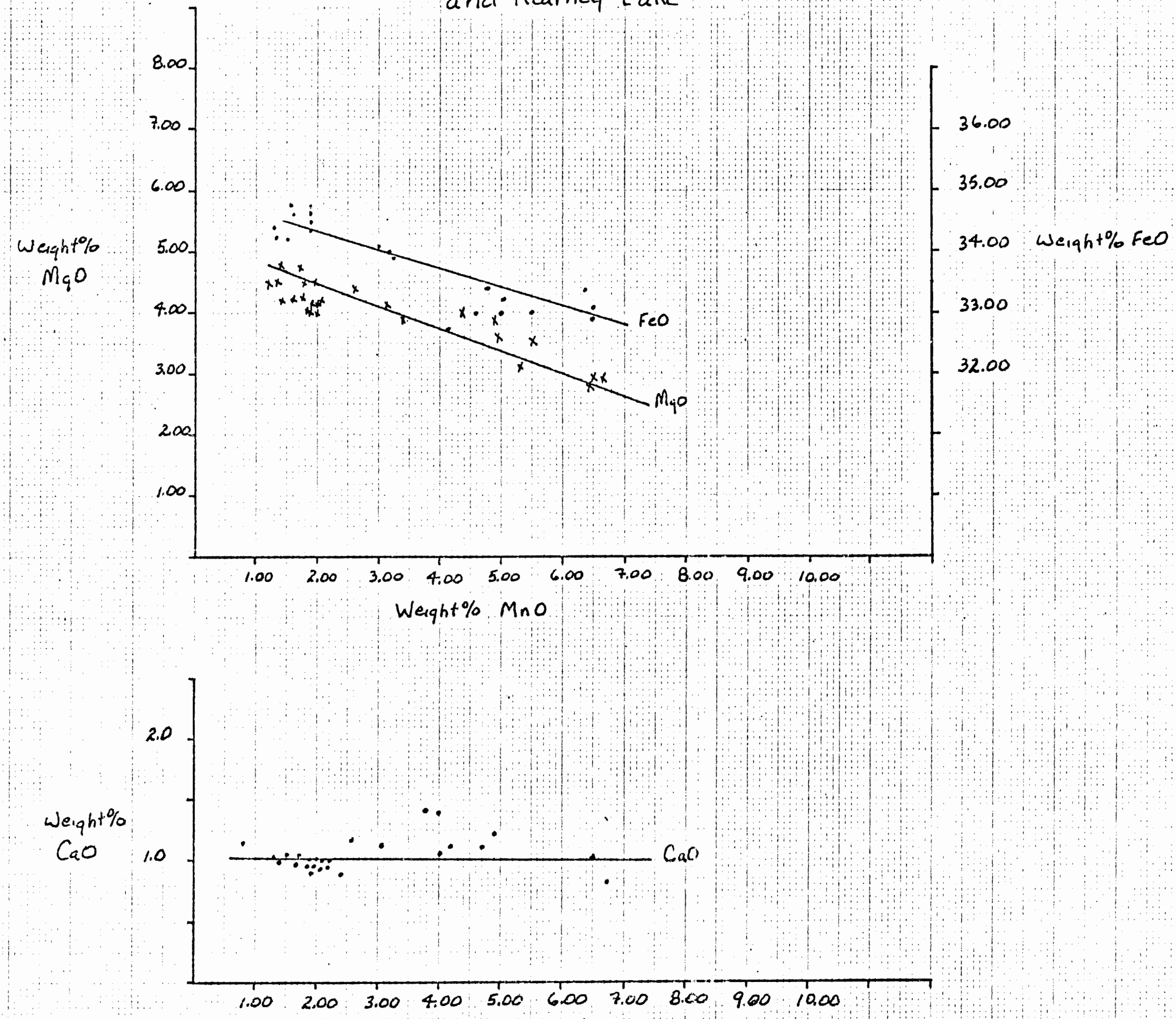


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Fig. 31 Mount Uniacke garnet analyses

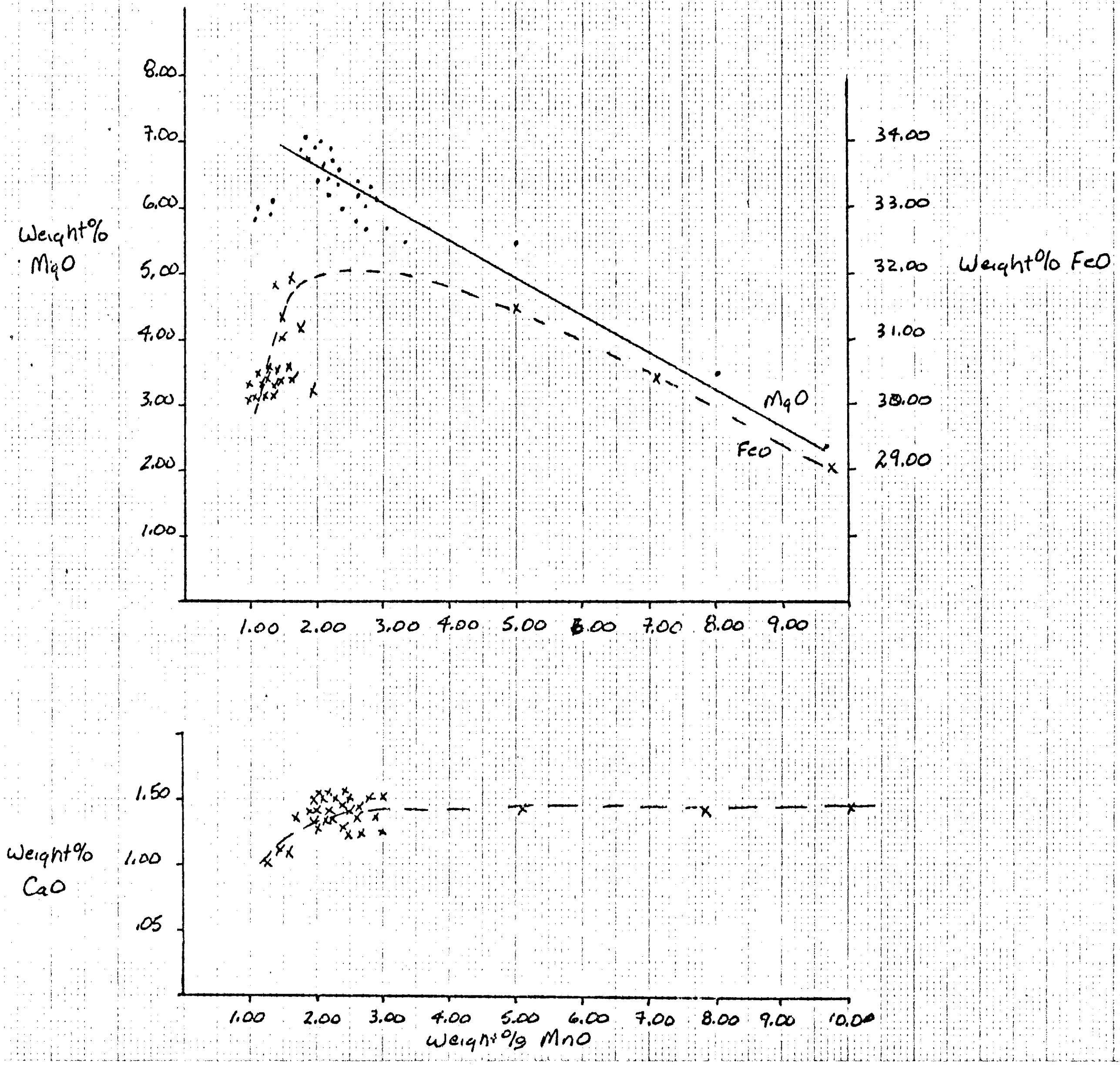

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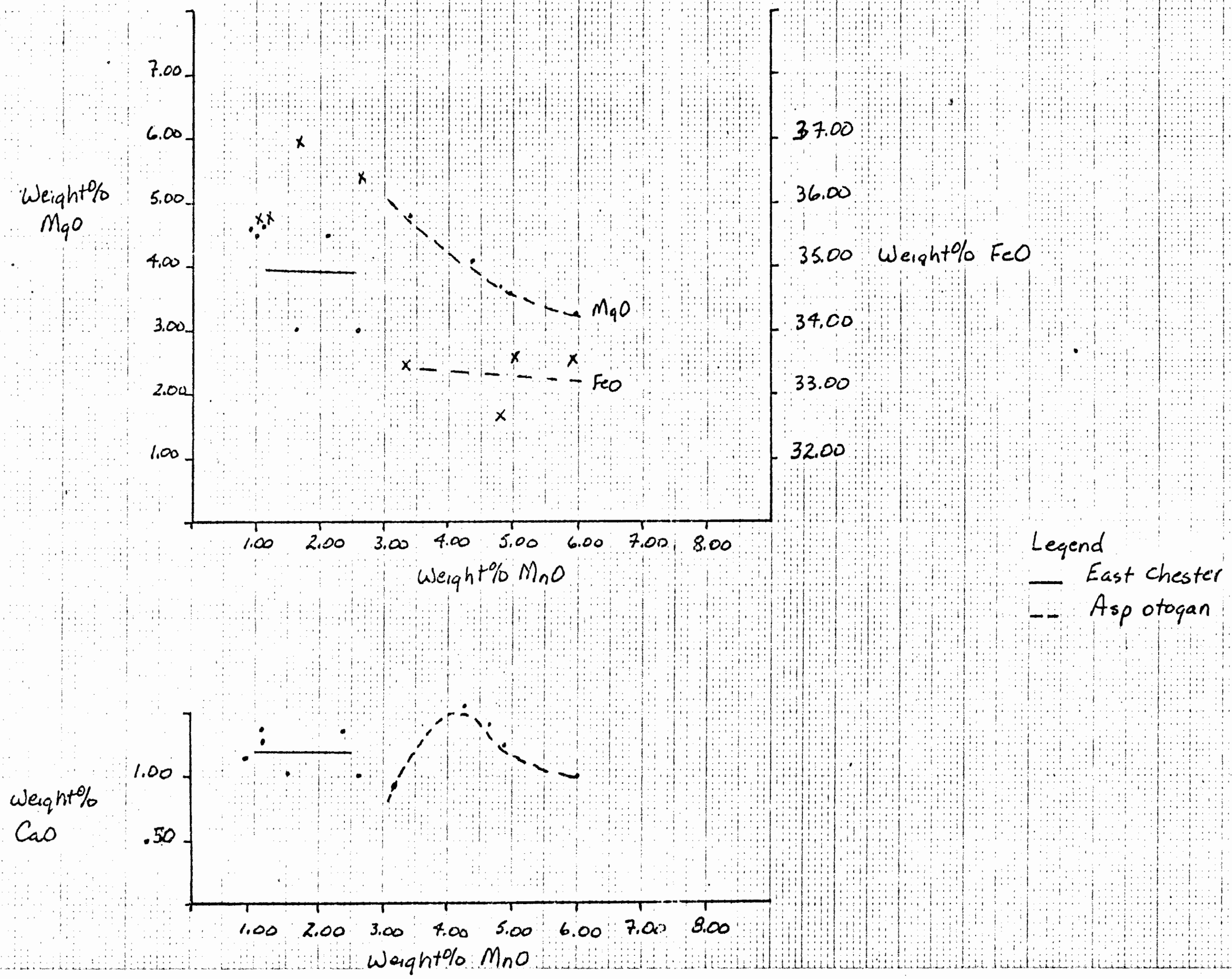
Fig. 32 Garnet analyses of East chester and Aspotogan



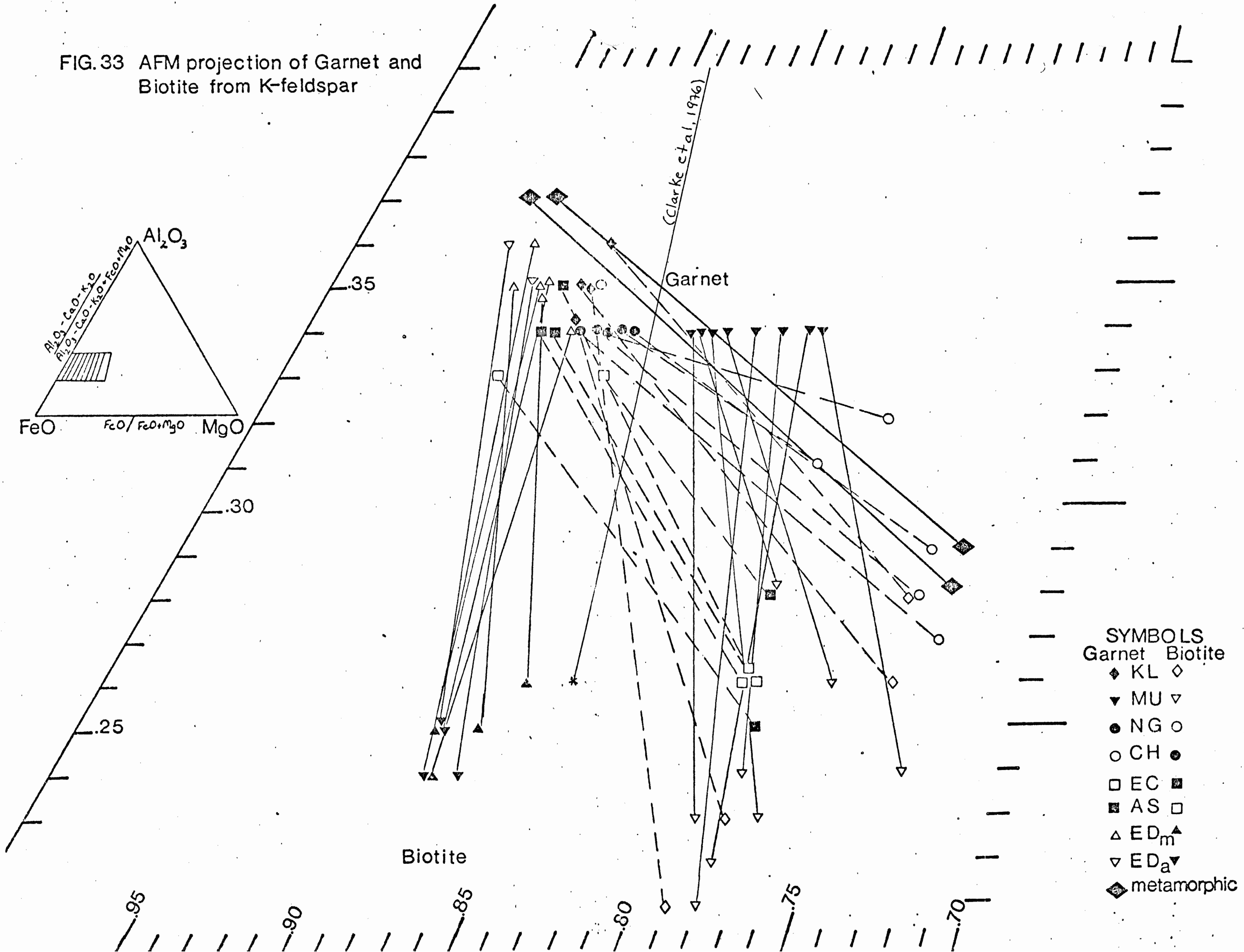
Since zoning was not investigated in Aspotogan, Mount Uniacke and East Chester samples, a comparison of Fig. 29 and 30 with Fig. 31 and 32 may permit inferences to be made regarding the type of zoning in these samples. From this comparison, garnets from Mount Uniacke (Fig. 31) may be reversely zoned, but garnets from East Chester or Aspotogan (Fig. 32) lack enough control points to define any pattern.

Reverse zoning of the garnets from Mount Uniacke would agree with the profiles of Mount Uniacke garnets produced by Jamieson (1974).

## 4.5 AFM Diagram

Coexisting garnet and biotite compositions of each sample location are plotted in the AFM system (Thompson, 1957) projected from alkali-feldspar (Fig. 33). Also plotted on this diagram are an average andalusite ~~and~~ biotite coexisting pair from the monzogranite (Clarke et al, 1976) and a metamorphic garnet-biotite coexisting pair from the metasediments surrounding the batholith in the Shelburne area of Nova Scotia (McKenzie, unpublished).

FIG. 33 AFM projection of Garnet and Biotite from K-feldspar



## Chapter 5 DISCUSSION

The garnets in this study can be subdivided into three distinctive textural groups, the properties of which are summarized in Table 4.

### Group I

Garnets in this group are spessartine-poor and pyrope-rich anhedral grains which are normally zoned and have an extensive reaction rim of biotite. They are always associated with xenoliths (Table 4).

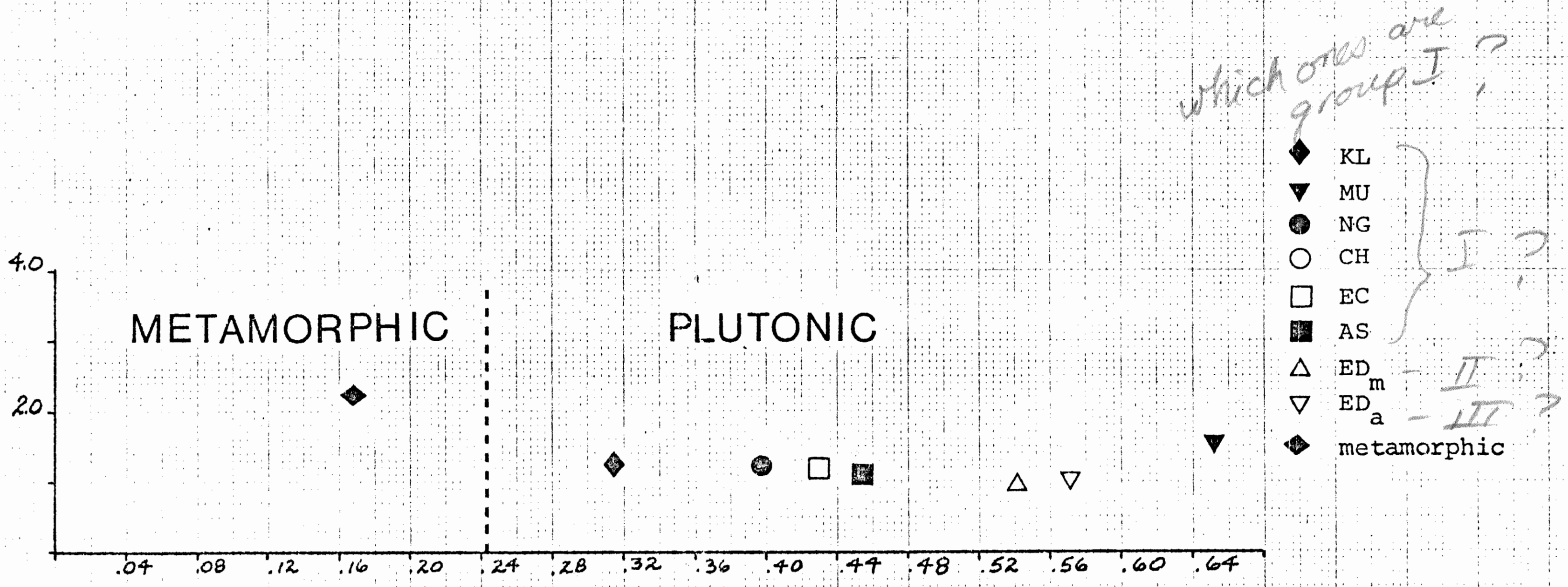
The garnet-biotite textures indicate that garnet was being replaced by biotite in a reaction relationship liquid + garnet → biotite. Normal zoning is a feature which is widely accepted as being produced by progressive metamorphism of sediments (Atherton, 1968; Kretz, 1973) and thought by some authors to be a characteristic feature of it (Green, 1977). Spessartine content of less than 10% has been shown by Stoddard and Miller (in press) to be unlike the majority of garnets crystallized from a granitic liquid. The position of Mg/Fe $K_{D_{garnet-biotite}}$ values on Hsu's (1968) diagram for Group I are all near the metamorphic-plutonic division line (Fig. 34), and the tie lines of coexisting biotite-garnet pairs in the AFM system parallel metamorphic tie lines and biotite analysis fall on the Mg side of an arbitrary line in Fig. 37 (labelled xy). The association of this group with xenoliths may indicate that the garnet was produced as a stable mineral during contact metamorphism

How does the affect Mn/F partitioning?

actually shows broad spectrum w/in Gp I or I don't understand diagram

METRIC

Fig. 34 Mg/Fe $K_{D\,garnet\text{-}biotite}$ Values of Analysis



which ones are group I ?

I ?

II ?

III ?

Table 4 Summary of Textural Group Characteristics

| Texture Type | Group I | Group II | Group III |
|---|---|---|---|
| Sketch | Figs. # 15 & 16 | Figs. # 17 - 21 | Figs. # 22 -23 |
| Description | anhedral garnet cores mantled by biotite | biotite cores in sub-euhedral garnets | small euhedral garnets |
| Assoc. with xenolith? | Yes | No | No |
| Chemistry | low manganese<br>2-4% MnO<br>high magnesium<br>4-6% MgO | high manganese<br>6% MnO<br>low magnesium<br>3% MgO | highest manganese<br>7% MnO<br>low magnesium<br>2% MgO |
| Zoning | normal | reverse | reverse |
| Mg/Fe values $K_{D\,garnet-biotite}$ | more metamorphic in character | plutonic | plutonic |
| AFM | biotites on Mg side of xy line, Fig. 37<br>tie line parallel with metamorphic tie line | biotite on Fe side of xy line<br>tie line steeply cuts metamorphic tie line | biotites on Fe side of xy line<br>tie line steeply cuts metamorphic tie line |

Table 4 (cont'd)

| Texture Type | Group I | Group II | Group III |
|---|---|---|---|
| Host rock type | mainly granodiorite<br>minor monzogranite | monzogranite | mainly leucocratic monzogranite<br>very minor monzogranite |
| Localities | Mount Uniacke, Kerney Lake, East Chester, New Germany, Aspotogan | East Dover | East Dover |

what difference?

(Hyndman, 1972) and then began to react as assimilation of the incorporated sedimentary material took place by the granodiorite (Bowen, 1937).

A metamorphic origin of Group I is supported by a study of xenoliths along the South Mountain batholith contact which indicated that xenoliths were indeed metamorphosed to a pyroxene-hornfels facies, with garnet being part of the stable metamorphic assemblage (Jamieson, 1974).

Hence, Group I is envisaged as representing garnets which have been produced from the progressive metamorphism of incorporated sedimentary fragments. During assimilation of the xenolith, garnet became unstable and reacted with the liquid to form biotite. Extensive reaction rims of biotite may have isolated garnet from the liquid, allowing it to remain as a refactory phase after the xenolith had completely or partially assimilated.

Group II

Group II ~~are~~ includes reversely zoned, euhedral garnets which are rich in spessartine and poor in ~~g~~pyrope. The garnets have a biotite core and are found in a non-xenolithic xenolith-free monzogranite host rock (Table 4).

Spessartine concentrations of greater than 10% suggest the stability and crystallization of garnet in a granitic liquid (Green, 1977; Stoddard and Miller, in press), owing to the possible enrichment of manganese due to differentiation (Goldschmidt, 1954; Fig. 13). Reverse zoning and an euhedral crystal shape are characteristics which Green and Ringwood (1968) attribute to magmatic garnets. Mg/Fe $K_{D_{garnet-biotite}}$ values that are more plutonic for Group II may signify they are more igneous in character than Group I (Fig. 34). Also, the AFM tie lines of Group II steeply cut across the tie lines of Group I and the metamorphic samples, and biotite analyses are on the Fe side of line xy (Fig. 37). A lack of associated xenoliths with this group precludes an obvious xenocrystic origin of garnets, and the biotite-garnet texture may express the relationship liquid + garnet → biotite, liquid + biotite → garnet or liquid → garnet + biotite. The position of Group II on Green's (1977) diagram also indicates crystallization from a granitic melt (Fig. 35 and 36).

see previous comment re Fig 34

It is concluded that Group II garnets result from ~~is a feature of~~ primary crystallization from a liquid in which the meaning of the textural relationship between biotite and garnet is unclear.

## Group III

This group includes spessartine-rich garnets which are euhedral ~~in shape~~ and inclusion free. They are found almost exclusively in a leucocratic monzogranite aplite and rarely in a monzogranite host rock (Table 4).

Fig. 35 Garnet Analysis in Diagram by Green (1977)

so what ?

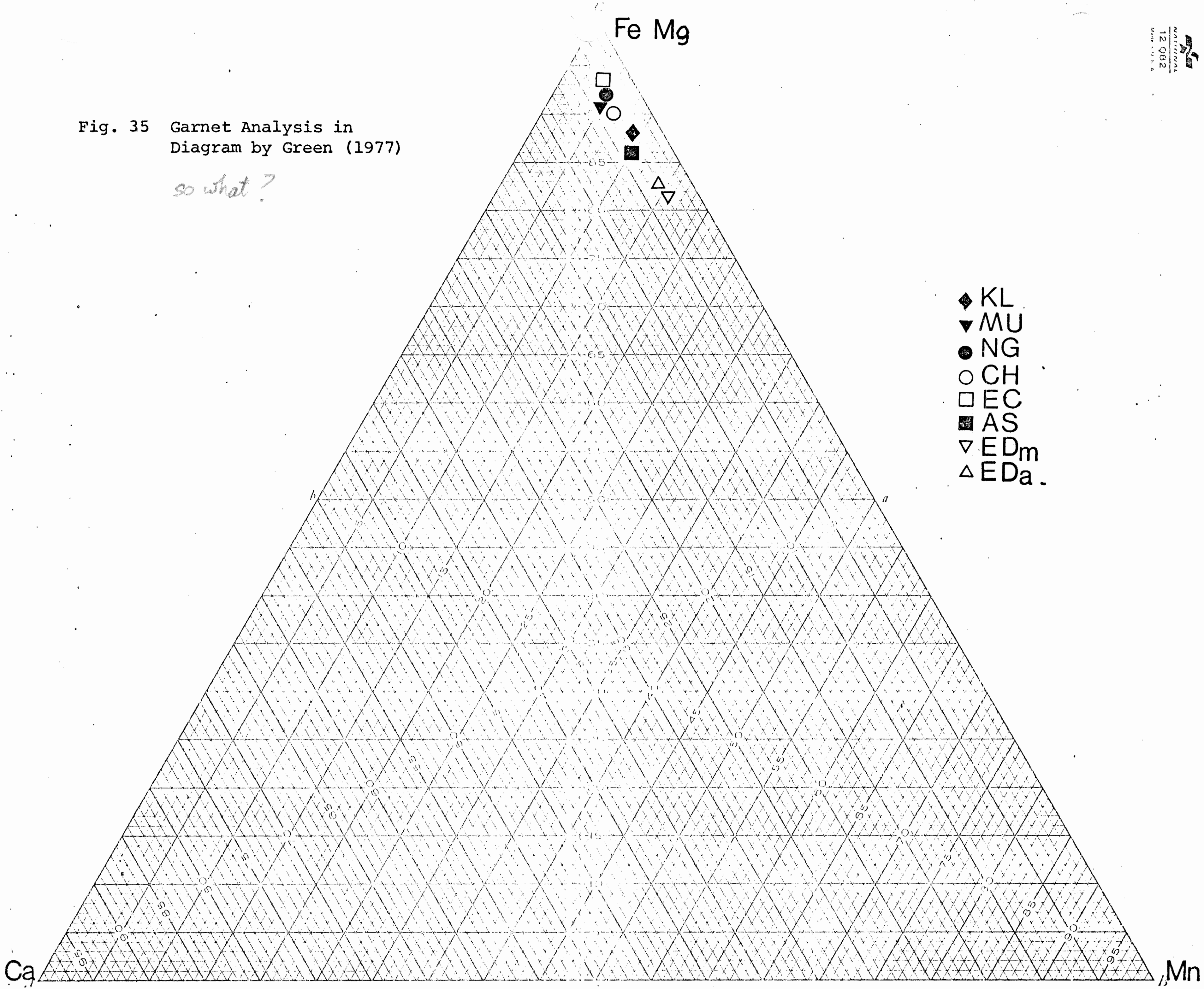


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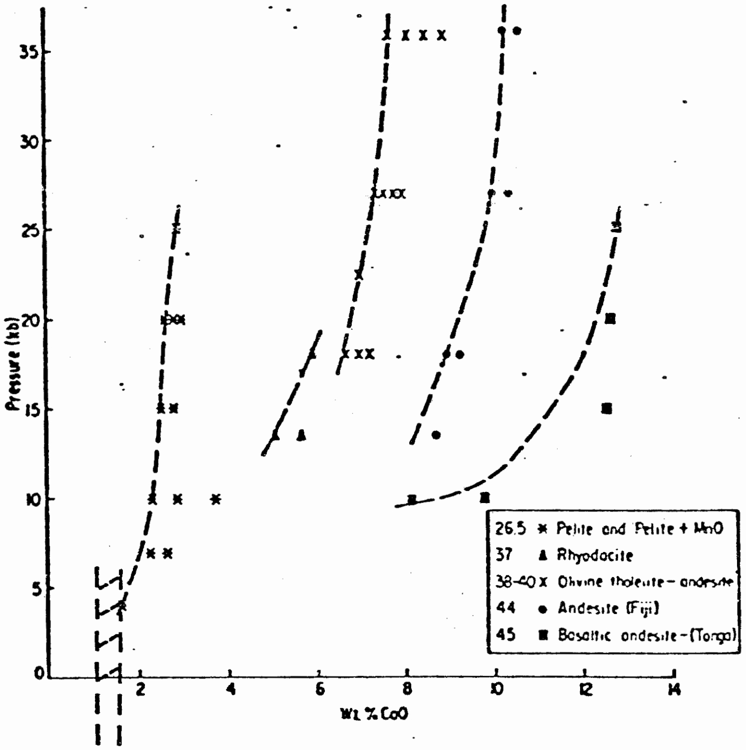
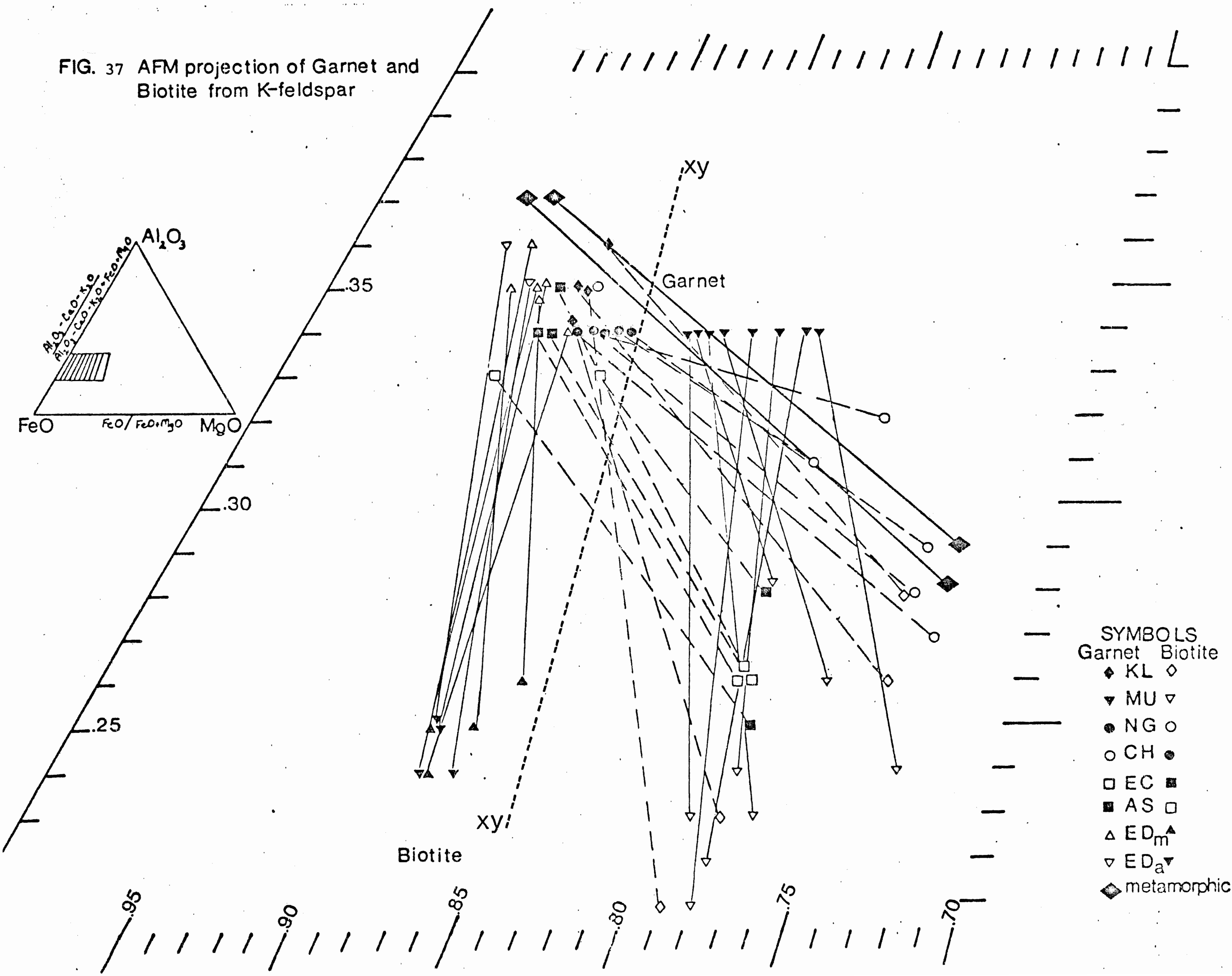
Fig. 36 Weight Percent CaO as Indicator of Source Material



SMB Garnets

FIG. 37 AFM projection of Garnet and Biotite from K-feldspar



Birch and Gleadow (1974), Green and Ringwood (1968), Green (1977) and Stoddard and Miller (in press) would ascribe an inclusion free, euhedral habit of a spessartine-rich garnet to an equilibrium crystallization of garnet, stabilized in a granitic liquid by an increase of manganese during differentiation. The AFM tie lines of Group III are not parallel to either Group I or the metamorphic pair, but are identical to Group II (Fig. 33). However, Mg/Fe $K_{D\,garnet-biotite}$ values for Group III are more "igneous" than Group II (Fig. 34). The texture of garnet and biotite in Group III defines the relationship liquid → garnet + biotite. X

The interpretations of each group would suggest that garnets of Group I are metamorphic and those of Groups II and III crystallized directly from a granite liquid.

supports a model of ?

Information regarding Group III denotes equilibrium crystallization of a garnet in a leucocratic monzogranite liquid which had enough Mn to stabilize garnet.

## Chapter 6 AFM AND THE LIQUIDUS MODEL

If the AFM liquidus relationship for the South Mountain batholith does exist as proposed by Abbott and Clarke (1979, emng of Fig. 9), the magmatic AFM mineral assemblages should define the predicted equilibrium path of the liquid as it crystallized. Therefore, using primary andalusite analyses from monzogranite (Clarke et al, 1976) and ? only analyses of primary monzogranite garnets from in this study (Group II and III), the liquidus path would, in fact, be defined under falling temperature as andalusite + biotite → liquid (+gn+ t), andalusite + biotite arrows + garnet → liquid, and garnet + biotite → liquid (+and); with the garnet/andalusite/biotite reaction point being limited by A = .34-.28 and F = .89-.86 (Fig. 38). This provides good evidence that area emng of Fig. 9 may apply to the monzogranites of the South Mountain batholith.

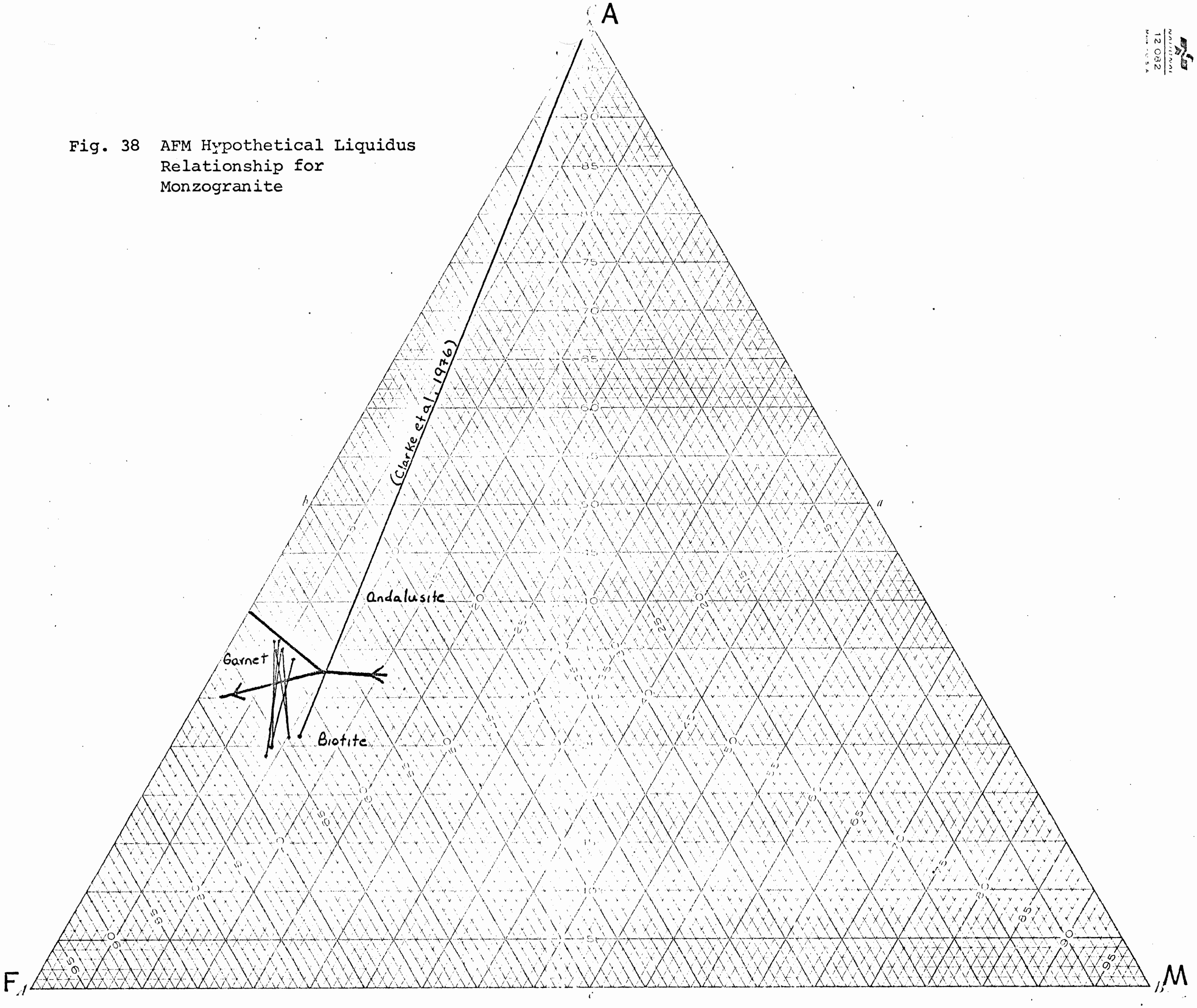


Fig. 38 AFM Hypothetical Liquidus Relationship for Monzogranite

## Chapter 7 CONCLUSIONS

All the garnets formed in the South Mountain batholith are almandine-rich with varying subordinate amounts of pyrope and spessartine, and minor grossular.

Garnet in the granodiorite phase of the South Mountain batholith is an unstable mineral, formed during the progressive metamorphism of country rock fragments which were incorporated into the melt. Garnet may have been isolated from assimilation by the liquid by an extensive reaction rim of biotite and remained in areas as a refractory phase in xenoliths partially or completely recrystallized to a granodiorite texture and mineralogy. The presence of garnet may also mean the liquid was removed before the reaction liquid + garnet → biotite could reach completion.

In monzogranite and leucocratic monzogranite aplite bodies, garnet crystallized directly from the liquid. The enrichment of manganese in the liquid by differentiation allowed garnet to stabilize, but manganese levels in the monzogranite were not high enough to completely stabilize almandine during the entire period of crystallization. However, garnet in leucocratic monzogranite aplite dykes were was in equilibrium with the magma throughout crystallization as evidenced by the texture. The texture al relationship of garnet-biotite of Group II is very difficult to interpret.

The plot of coexisting magmatic minerals of monzogranite (Groups II and III) in the AFM system may define the path of the liquid during crystallization as andalusite + biotite → liquid, garnet + andalusite + biotite → liquid, garnet + biotite → liquid and locates the garnet/andalusite/biotite reaction point by the limits A = .28-.34 and F = .86-.89; This supports supplying evidence for the hypothetical relationship proposed by Abbott and Clarke (1979).

arrows

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## Time Allotment

| | |
|---|---|
| Field work | 35 hr. |
| Sample preparation | 20 hr. |
| Microprobe time | 40 hr. |
| Data processing | 200 hr. |
| Library time | 30 hr. |
| Writing | 150 hr. |
| TOTAL | 475 hr. |

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