

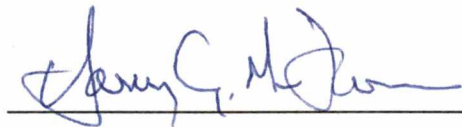
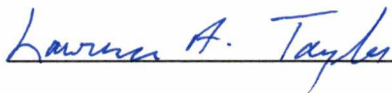
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I am submitting herewith a thesis written by Milo L. Cameron entitled "Garnet Zoning, Mineral Inclusions, and P-T Paths: Evidence for a Polymetamorphic History of the Cullowhee Gneiss." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.

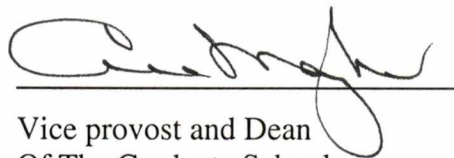


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We have read this thesis
and recommend its acceptance:



Accepted for the Council:



Vice provost and Dean
Of The Graduate School

**Garnet Zoning, Mineral Inclusions, and P-T Paths: Evidence
for a Polymetamorphic History of the Cullowhee Gneiss**

A Thesis
Presented for the
Master of Science Degree
The University of Tennessee, Knoxville

Milo Louis Cameron
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Abstract

Detailed quantitative and qualitative x-ray maps of garnets from the Cullowhee Gneiss, Cullowhee, North Carolina indicate a complex metamorphic history. The Cullowhee Gneiss is a migmatitic quartzo-feldspathic gneiss with boudins of amphibolite and quartz. Thin-sections from the same outcrop have the same major mineral assemblage which includes biotite + muscovite + plagioclase + quartz + sillimanite + kyanite + garnet. Three garnets, with diameters that range from 7mm to 1.4 cm, taken from the same outcrop, contain inclusions of biotite + rutile + ilmenite + quartz + muscovite + K-feldspar + plagioclase + apatite + monazite and sillimanite needles in the rims. These inclusions indicate that at one time the metamorphic conditions were at the second sillimanite isograd and above the muscovite breakdown point.

Garnet zoning patterns are the result of both diffusion and growth processes and indicate that early garnet compositions were altered along the rims, cracks, and large fractures during a later period of metamorphism. The fracturing of the garnet created asymmetry in one zoning profile, an atoll effect in another sample that is most visible in the grossular content of the garnet. End-member zoning profiles of the garnets have an increase in grossular, almandine, and spessartine content, towards the core, while the pyrope profile decreases towards the core. In garnets that have the atoll of high calcium, there is a break in all the profiles and it is harder to distinguish the shape of the original profiles. Flattened profiles, towards the center of the garnet, indicate that diffusion processes had a dominant influence on the original zoning profiles. The larger garnet has an euhedral core encased by an anhedral overgrowth of garnet. The overgrowth contains very few inclusions, but has fluid inclusion trails. There is a great contrast between the

An content of plagioclase inclusions at the cores (An_{35-40}), the high calcium ring (atoll) (An_{40-66}) outside the core, and the An content in the matrix (An_{23}). These contrasts reflect the differences in the P-T conditions during different metamorphic events.

Thermobarometry indicates an early high -pressure (~ 7.5 kbars) high - temperature ($\sim 620^\circ\text{C}$) period within the garnet's core. At this stage in the garnet's history, diffusion processes were dominant in determining the type of zoning profile. Depressurization resulted in the crossing into the sillimanite field. During this stage, growth zoning dominated the chemical zoning patterns of the garnet and an overgrowth of garnet had plagioclase with lower anorthite content, a pressure drop (to 5 kbars) and a decrease in temperature. The final period of metamorphism produced rim conditions with An_{23} and pressures (~ 4 kbars) and temperatures (475°C).

P – T paths calculated with the GIBBS program by Spear and Kohn, (1997) are clockwise, as is typical of overthrust terranes. They indicate that there was an overprint of a high-pressure metamorphic event by a high temperature event that went above the muscovite breakdown curve. There was decompression and cooling during the retrograde path, and finally an increase in pressure with a decrease in temperature at the rim of the garnet.

The garnets of the Cullowhee Gneiss recorded the polymetamorphic history of the Eastern Blue Ridge Province. This history spans the Grenville, Taconian, Acadian, and Alleghanian, orogenies.

Table Of Contents

Chapter	Page
I Introduction	1
Geologic Setting.....	2
Intensity and Timing of Metamorphic Events	6
Study Location	9
Previous Studies	14
Analytical Methods	14
II Mineral Assemblages	20
Mineral Composition	26
AFM Phases	44
II Garnet Zoning	49
Micrographs	54
Semiquantitative Images	61
Zoning profiles	63
IV Thermobarometry	68
Introduction	68
Pressure – Temperature Paths	81
Pressure – Temperature Paths from Zoned garnets	86
V Discussion and Conclusion	94
Discussion	94
Conclusion	100
References Cited	102
Appendices	111
1a Sample 1: Qualitative X-ray images	112
1b Sample 1: Qualitative Masks	116
1c Sample 1: Micrographs	121
1d Sample 1: Computer Code	130
2a Sample 2: Qualitative X-ray images	134
2b Sample 2: Qualitative Masks	138
2c Sample 2: Micrographs	142
2d Sample 2: Computer Code	150

3a Sample 3: Qualitative X-ray images	154
3b Sample 3: Qualitative Masks	159
3c Sample 3: Micrographs	162
3d Sample 3: Computer Code	168
4a Sample 1 Garnet Electron Microprobe Analyses	172
4b Sample 2 Garnet Electron Microprobe Analyses	178
4c Sample 3 Garnet Electron Microprobe Analyses	189
5a Sample 1 Biotite Electron Microprobe Analyses	204
5b Sample 2 Biotite Electron Microprobe Analyses	206
5c Sample 3 Biotite Electron Microprobe Analyses	209
6a Sample 1 Plagioclase Electron Microprobe Analyses	214
6b Sample 2 Plagioclase Electron Microprobe Analyses	218
6c Sample 3 Plagioclase Electron Microprobe Analyses	223
7b Sample 2 Ilmenite Electron Microprobe Analyses	231
7c Sample 3 Ilmenite Electron Microprobe Analyses	234
8a Sample 2 K-feldspar Electron Microprobe Analyses	236
8b Sample 3 Muscovite Electron Microprobe Analyses	236
9 Mineral Abbreviations	236

List of Tables

Table	Page
2.1 Mineral Compositions. a) Sample 1. b) Sample 2. c) Sample 3.....	28
2.2 Range of formula proportions in the Cullowhee Gneiss. a) Biotite, muscovite, and ilmenite. b) Garnet and plagioclase.....	31
4.1 Temperature and pressure values for the three samples studied relative to the regions of the garnet.....	71
4.2 Comparison of the intersection values for different thermometers and barometers for Samples 2 and 3 that were used to create Figures 4.2(a-b)...	80

List of Figures

Figure	Page
1.1 Regional Tectonic map of the Southern Appalachians.....	4
1.2 Regional metamorphic isograd map of the Southern Appalachian Mountains.....	7
1.3 Location of the outcrop within the Silva South field area.....	10
1.4 The outcrop on Highway 107 where the samples were collected.....	13
1.5 All four images are qualitative x-ray maps of Sample 3 that were pieced together in the program Transform. a) The Fe x-ray image. b) The Mg x-ray image. c) The Mn x-ray image. d) The Ca x-ray image.....	16
2.1 Photomicrograph. a) Sample 1. b) Sample 2. c) Sample 3.....	21
2.2 Photomicrograph of Sample 3 with artistic enhancement that shows the perpendicular microfractures, the radial sillimanite, and the tangential sillimanite.....	25
2.3 Kyanite and sillimanite in the matrix of Sample 3.....	27
2.4 Histogram of the mole fraction garnet. a) Almandine and pyrope. b) Grossular and spessartine.....	32
2.5 Garnet ternary diagram. a) Sample 1. b) Sample 2. c) Sample 3.....	35
2.6 Biotite Fe/(Fe + Mg) versus Titanium cation proportion for all biotite analyses....	39
2.7 Tetrahedral aluminum (⁴ Al) versus octahedral aluminum (⁶ Al) in biotite for the samples studied.....	40
2.8 The Fe/(Fe + Mg) versus Na + K values for the biotite analyses in the matrix, core, rim, and in the fractures for the samples of this study.....	41
2.9 Mole fraction grossular versus the mole fraction anorthite in the garnet and plagioclase pairs.....	43
2.10 Thompson AFM diagram for the samples studied.....	45
3.1 Garnet compositional profile and the corresponding micrograph for Sample 1.....	50
3.2 Garnet compositional profile and the corresponding micrograph for Sample 2.....	51

3.3	Garnet compositional profile and the corresponding micrograph for Sample 3.....	52
3.4	Qualitative images of Samples 1, 2, and 3 produced from the x-ray scans.....	55
3.5	Qualitative images of the Fe/(Fe + Mg) ratio for Samples 1, 2, and 3.....	57
3.6	Some of the images that were created from the mineral masks used to reproduce the thin section of Sample 3	58
3.7	Rebuilding of the thin section for Sample 3. a-b) High and low Ca zones. c-d) Placing of biotite. e-f) Placing of plagioclase.....	60
3.8	Sample 1 semiquantitative analyses. a) The grid used to locate the quantitative microprobe data. b) Fe/(Fe+Mg) semiquantitative image. c) Semiquantitative image of the Ca/(Ca+Na) content in plagioclase.....	62
4.1	Thermobarometry. a) Comparison between the core and rim for Sample 1. b) Comparison between the core and rim for Sample 2. c) Comparison between the core and rim for Sample 3.....	72
4.2	Compared thermobarometry. a) Sample 2. b) Sample 3.....	77
4.3	Relative P-T paths. a) Sample 1. b) Sample 2. c) Sample 3.....	82
4.4	Calculated P-T paths from garnet zoning. a) Sample 1. b) Sample 2. c) Sample 3.....	90

I. Introduction

The metamorphic rocks that compose orogenic belts, such as the Appalachian Mountains, can be the result of several tectonic events. The pressure and temperature conditions that the rocks experienced during each metamorphic event can sometimes be preserved in the minerals of the rocks. The new mineral assemblages contain clues about the metamorphic conditions under which they were formed. Within these mineral assemblages are compositionally zoned minerals, such as garnet and plagioclase, which can record the history of their growth.

Compositional zoning in minerals is the result of porphyroblast growth and diffusional processes during changing pressure and temperature conditions (Spear and Selverstone, 1983; Tracy et al., 1976). Garnet is the mineral most commonly studied because it is found in many kinds of rocks, has a composition that is sensitive to pressure and temperature changes, and has low diffusion coefficients so that zoning profiles are commonly preserved (Yardley, 1977; Robinson, 1991; Spear, 1983; Tuccillo, 1990). The kind of zoning profile produced in a garnet is a function of bulk-rock composition, continuous reactions, homogeneous diffusion rates, pressure and temperature conditions at the time of metamorphism, and the metamorphic fluids, if any, which were involved in the reactions (Tracy and Robinson, 1976). If there was only one metamorphic event, then the study of garnet would be the deciphering of one zoning profile in terms of the P-T conditions over which the garnet grew. Unfortunately, retrograde effects on the garnet, along with any resetting of the garnet's zoning profile because of polymetamorphism, compound the problem of deciphering metamorphic history.

Two objectives of my study are

- (1) To analyze the complex zoning patterns within the garnets of the Cullowhee Gneiss by using detailed qualitative x-ray data maps and quantitative zoning profiles analyzed with the electron microprobe (EMP). The maps and zoning profiles will be correlated with the polymetamorphic history.
- (2) To examine mineral inclusions within the garnet and to calculate P-T paths from garnet zoning.

Geologic Setting

The Southern Appalachian Mountains comprise a sequence of thrust sheets created by compressional forces that closed ocean basins during late Paleozoic times (Hatcher, 1972; Rankin, 1975). Among the large thrust sheets is the Blue Ridge thrust, which is an amalgamation of metaigneous and metasedimentary rocks that lie west of the Brevard fault and east of the Valley and Ridge province. The idea of the Blue Ridge as a composite thrust sheet evolved from the studies of windows that are part of the foothills of the Smoky Mountains (Hatcher and Goldberg, 1991).

The Blue Ridge can be subdivided into a westernmost imbricate thrust belt composed of unmetamorphosed to low-grade rocks of the Talladega belt, the Ocoee Supergroup, the Chilhowee Group, and basement rocks. The Blue Ridge has a core that contains higher grade Ocoee Supergroup rocks, Murphy-Belt rocks, older metasedimentary rocks, and basement rocks. The third division is the eastern belt, which is made of rocks from the Heard Group, the Ashland -Wedowee Group, the Tallulah Falls Formation, the Ashe Formation, and the Lynchburg Formation (Hatcher, 1978). The Great Smoky-Cartersville fault separates the unmetamorphosed rocks of the Valley and

Ridge from the Blue Ridge province at the western edge, and the Brevard Fault separates the Piedmont from the Blue Ridge on the eastern flank (Figure 1.1).

The Blue Ridge is divided into an eastern and western half by the Hayesville - Fries Fault (Hatcher 1978; 1979). There are at least three important distinctions between the rocks of the eastern and the western Blue Ridge:

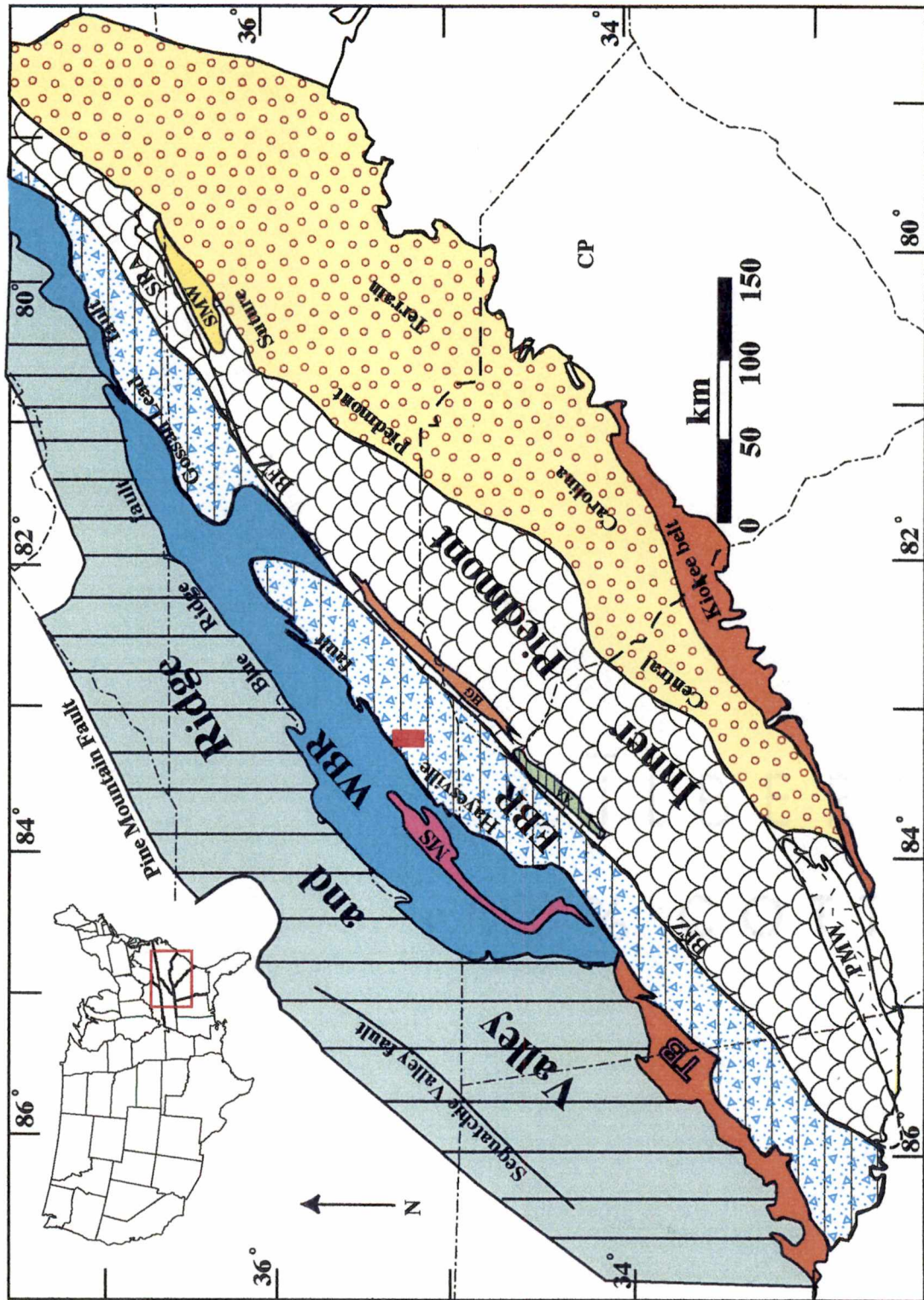
1. The western Blue Ridge has fewer rock types and smaller amounts of North American continental basement, while the eastern Blue Ridge province consists of a diverse juxtaposition of metasedimentary, metavolcanic, metaplutonic, and basement gneisses (Rankin, 1975; Hatcher, 1978, 1991).
2. The eastern Blue Ridge consists of sequences deposited on oceanic terrain while the rocks of the western Blue Ridge were deposited on North American continental basement (Rankin, 1975; Hatcher, 1978, 1991).
3. The eastern portion contains the metamorphic core while the western part is a lower-grade Barrovian sequence (Rankin, 1975; Hatcher, 1978, 1991).

The tectonic model for the Blue Ridge province of North Carolina, Tennessee, Georgia, and Virginia describes a series of continental rifting and continental collisions that started in the late Proterozoic and continued through Paleozoic times. The rifting started after the close of the Grenville Wilson cycle, and the sedimentary rocks record the complete Appalachian cycle and the beginning of the present Atlantic cycle. The model spans the Grenville, Taconian, Acadian, and Alleghenian orogenies (Hatcher, 1972; 1978; 1991; Rankin, 1975; Secor, 1986; Butler, 1972; Carpenter, 1970).

Early studies identified at least one metamorphic episode but did not distinguish among the multiple metamorphic events that affected the same rock units at different

Figure 1.1 (Next Page) Regional tectonic map of the Southern Appalachian Mountains. The rectangle shows the approximate location of the field area relative to the Blue Ridge Thrust (modified after Hatcher and Davis, 1993).

EXPLANATION: EBR = Eastern Blue Ridge; WBR = Western Blue Ridge; BFZ = Brevard Fault Zone; AA = Alto Allocthon; Hg =Hillabee Greenstone; TB = Talledega Belt; SMW = Smith Mountain Window; PMW = Pine Mountain Window; MS = Murphy Syncline
GMW = Grandfather Mountain Window



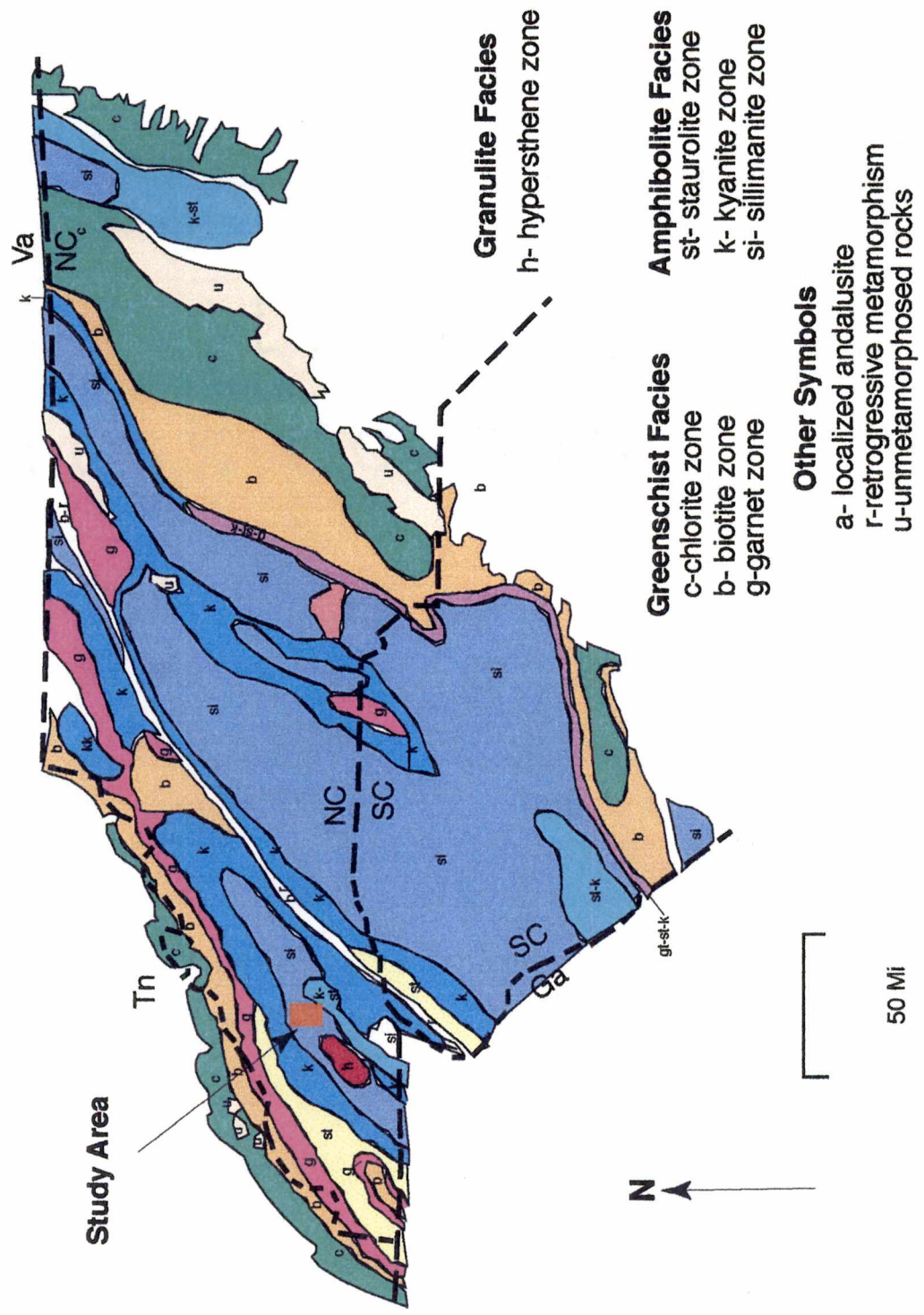
periods (Carpenter, 1970; Dallmeyer, 1975). More recent studies by Rodgers (1967, 1971), Fullager (1976), Butler (1972), and Carpenter (1970) indicated a complex metamorphic and deformation history within the Blue Ridge region. Carpenter (1970) delineated isograds over the Blue Ridge Province by mapping index minerals found in the sediment of streambeds. His work confirmed the earlier work by Hurst and Schlee (1962), Hadley and Goldsmith (1963), and King (1964), which described a classic Barrovian sequence in the Blue Ridge (Hatcher and Butler, 1979). The oversimplified metamorphic boundary map of Carpenter was revised by Hatcher and Butler (1979), shown in Figure 1.2, because studies of the rock units indicated a more complex history resulting from the telescoping of rock units from different deformational events (Hatcher, 1979).

Intensity and Timing of Metamorphic Events

Metamorphic grade increases eastward from the eastern boundary of the Valley and Ridge. At the Tennessee - North Carolina border (Figure 1.2), metamorphic grade is low chlorite grade, and metamorphic grade increases to granulite-facies conditions east of the Hayesville fault and decreases to garnet grade at the Brevard Fault (Hatcher and Butler, 1979; Absher and McSween, 1985). Bartholemew (1983) and Gulley (1985) suggested that the granulite-facies metamorphism in the Blue Ridge was Grenville in age, but Eckert (1985), Absher and McSween (1985), McSween and Hatcher (1985), and Kittelson (1988) argued that the granulite-facies metamorphism east of the Hayesville fault is Paleozoic in age.

The four dominant tectonic and metamorphic events in the Southern Appalachians occurred during the Grenvillian, Taconian, Acadian, and Alleghanian orogenies (Butler,

Figure 1.2 (Next Page): Regional metamorphic isograd map of the Southern Appalachian Mountains. The rectangle shows the approximate location of the field area (Modified after Butler, 1991).



1972; Dallmeyer, 1975; Hatcher and Butler, 1979). The dominant thermal event within the Blue Ridge occurred during the Paleozoic time. Butler (1972) proposed an age of 430 Ma for Taconian metamorphism, while Kish (1983) used whole rock K-Ar dating of slates to calculate an age of 480 Ma for the Taconic event. The two later metamorphic events occurred during the Acadian and Alleghanian orogenies.

The Acadian orogeny and related metamorphism was a low-grade overprint of the Taconian event (Glover et al., 1983). Sutter (1982) used $^{39}\text{Ar} - ^{40}\text{Ar}$ age dating of hornblende and biotite from metamorphic rocks of the Appalachian orogen to estimate the Acadian event at approximately 390 Ma. Butler (1982), using whole rock Rb-Sr dating of mylonites, determined a date of 410 ± 10 Ma. Dallmeyer (1988) used samples taken from the Tallulah Falls nappe to estimate a $^{39}\text{Ar} - ^{40}\text{Ar}$ date of ~ 322 Ma.

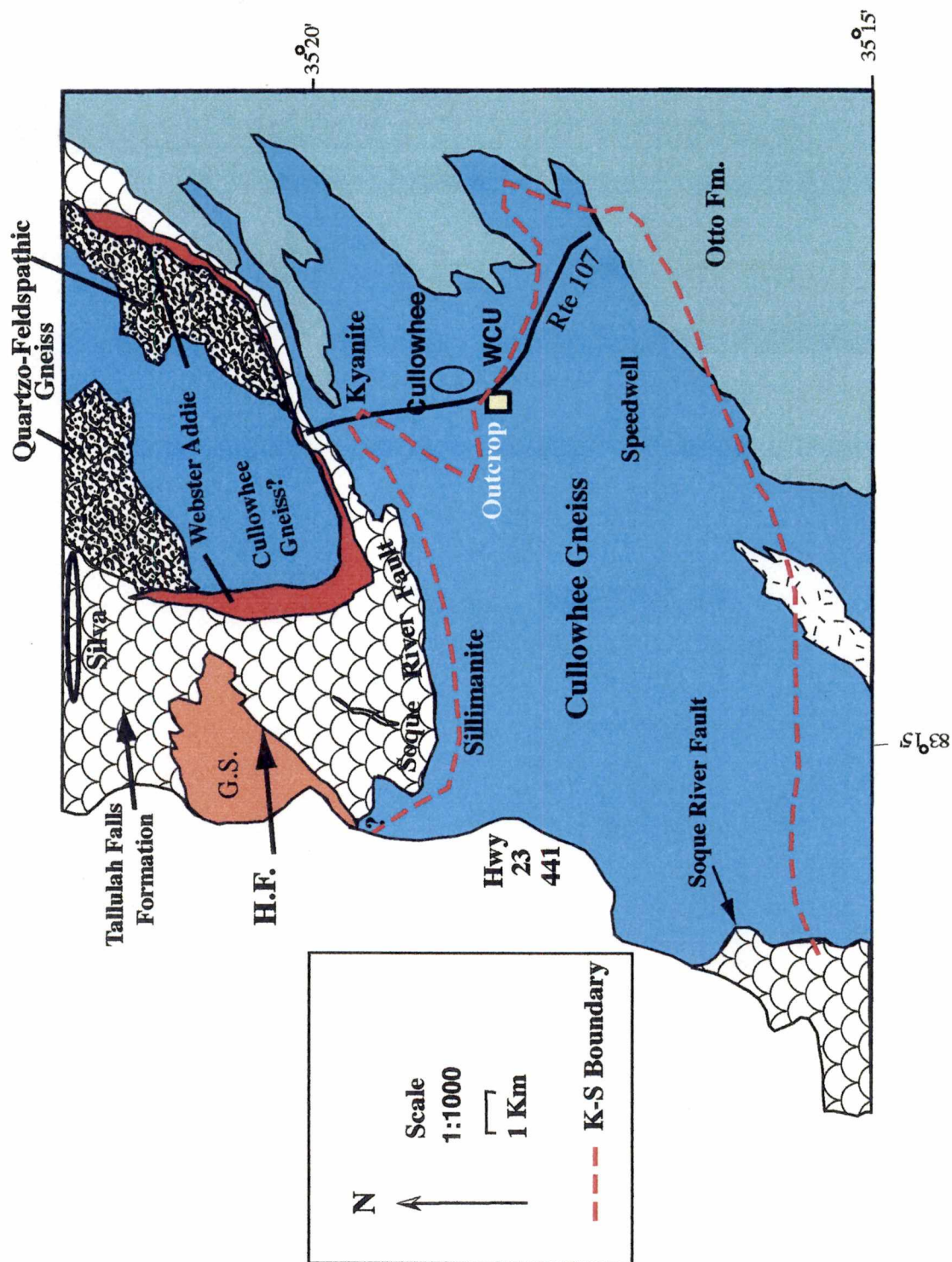
The studies done by Fullagar and Butler (1979) and Snoke (1980) in the Kiokee belt determined that another regional metamorphic event occurred after the Acadian orogeny. This changed the concept that the Acadian metamorphism was the youngest metamorphic event in the southern Appalachians, and a date of 250 to 300 Ma is given for the Alleghanian event (Glover, 1983; Sutter, 1982, Butler, 1982).

Study Location

The field area lies southeast of the Hayesville fault and is within the Silva South quadrangle. Figure 1.3 shows the field area location, the outcrop where the samples were collected from the Cullowhee Gneiss, and the important tectonic and metamorphic boundaries.

The two rock units of interest are the Otto Formation and the Cullowhee Gneiss. The Otto Formation consists primarily of a quartzofeldspathic gneiss and a coarse

Figure 1.3 Location of the outcrop within the Silva South field area. H.F. = Hayesville Fault; G.S. = Great Smoky Group. K = kyanite; S = sillimanite; WCU = Western Carolina University. The map is modified after Labotka and Shireman, 1991.



grained, two-mica schist. It contains less garnet than the Cullowhee Gneiss and is non-migmatitic. Near the contact with the Cullowhee Gneiss, the rocks of the Otto Formation contain a greater than average modal abundance of garnet and biotite (Davidson, 1995). The migmatitic Cullowhee Gneiss is primarily a garnet-biotite quartzofeldspathic gneiss that contains blocks, boudins, and lenses of amphibolite, calcsilicate, and minor ultramafic bodies.

Three faults are located within this area. The Hayesville Fault separates the Great Smoky Group of the Western Blue Ridge from the Tallulah Falls Formation and other rocks of the eastern Blue Ridge. The Soque River Fault separates the Tallulah Falls Formation from the Cullowhee Gneiss. The contact between the Cullowhee Gneiss and the Otto Formation is probably a fault surface (Figure 1.3) but the relationship between this fault and the Soque river fault is unknown.

The field area lies within the metamorphic core of the Blue Ridge. The dashed line on Figure 1.3 represents the sillimanite isograd. The isograd was mapped by Labotka and Shireman (1991) and is based on the occurrence of prismatic sillimanite within the rocks of the field area.

Figure 1.4 is a photograph of the outcrop where the samples were collected on highway 107 west of Western Carolina University. The rocks from this location represent the typical sample of the Cullowhee Gneiss (Davidson, 1995), and there is an abundant supply of garnets of varying sizes (< 1 mm to $>> 1$ cm) within the rock. From the samples collected, 127 thin sections were made. On the basis of the number of mineral inclusions, size of the garnets, and quality of the sample, five thin sections were chosen for electron microprobe (EMP) analyses.

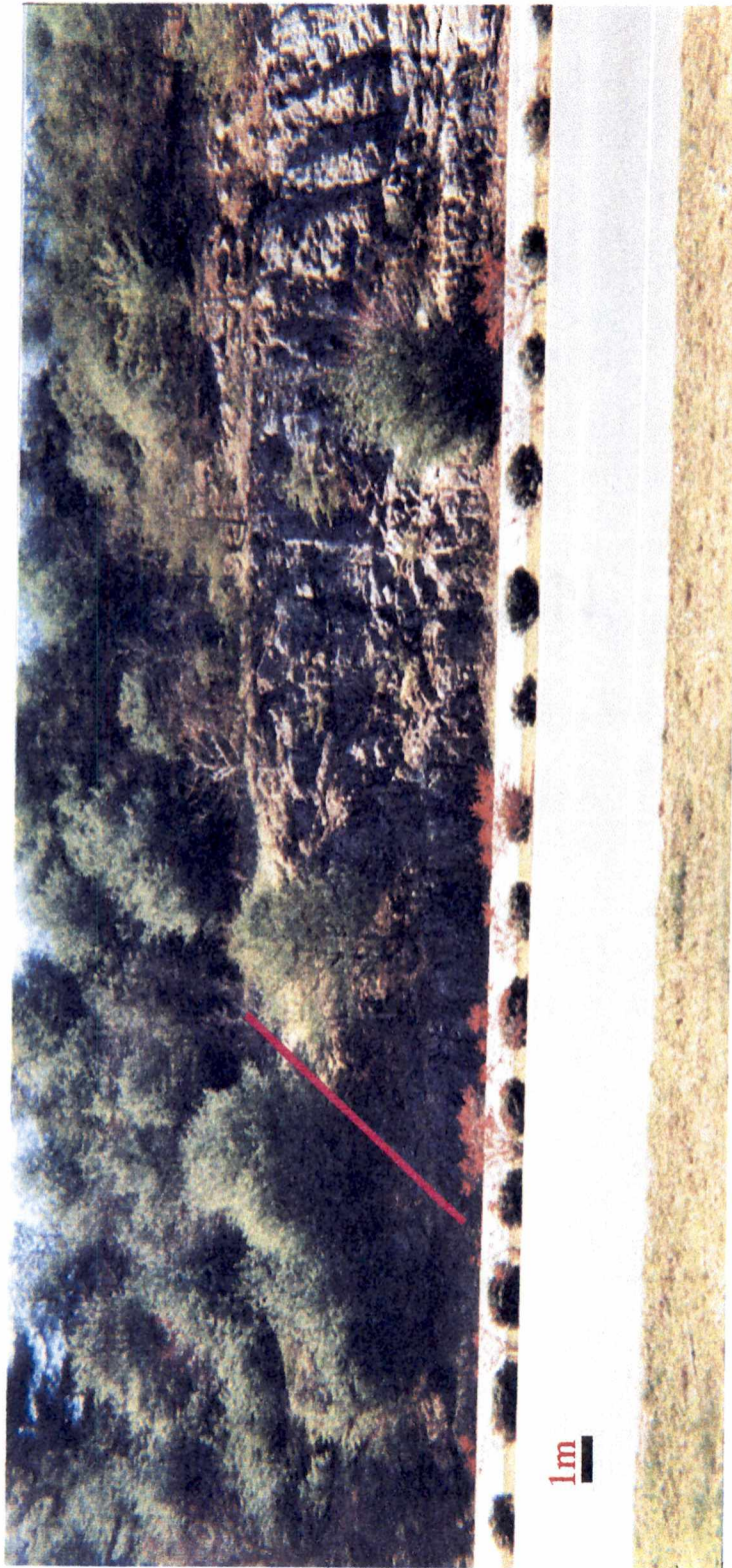


Figure 1.4 The outcrop on Highway 107 where the samples were collected. The Red line is a line of high garnet concentration within the outcrop.

Previous Studies

Kittleson (1988) studied the petrology of the Corbin Knob Quadrangle and the southeastern portion of the Franklin Quadrangle and determined that the structural history of the amphibolite and granulite terranes were similar and, therefore, that the granulite facies metamorphism was part of the regional Paleozoic metamorphic event.

Temperature and pressure were estimated at 580-680 °C and 5.5-6.8 kbars in the amphibolite facies and at 680-780 °C and 6.5-8.5 kbars in the granulite terrane. Eckert (1989) studied the petrology and structure of the Wayah Bald Quadrangle and delineated a series of prograde metamorphic zones. Absher (1984) studied the petrology and structure of the granulite facies terrane at Winding Stair Gap and determined that a prograde metamorphic event with a temperature range of 750 °C – 775 °C and pressures of 6.5 - 7.0 kbars existed during the peak metamorphic event. Shireman and Quinn mapped in the Silva North and South Quadrangles and around the Webster Addie ultramafic body. Davidson (1995) delineated the rocks of the Silva South Quadrangle and found that the Cullowhee Gneiss had a polymetamorphic history. The Cullowhee Gneiss had peak temperature and pressure conditions of $750 \pm 20^{\circ}\text{C}$ and 7.3 ± 1 kbars, while the Otto Formation had a single prograde metamorphic event and had peak metamorphic conditions of $530 \pm 20^{\circ}\text{C}$ at 4 ± 1 kbars.

Analytical Methods

Mineral compositions were determined with the Cameca SX 50 electron microprobe using natural and synthetic standards. Quantitative and qualitative analyses were obtained on three thin sections. For the quantitative analyses, an accelerating voltage

of 15 kV was used on all analyses. A beam current of 0.030 μA and a beam diameter of 5 μm were used for garnet, ilmenite, and rutile analyses. A beam current of 0.020 μA and a beam diameter of 10 μm were used in the analyses of mica and feldspar. Quantitative analyses were obtained with the use of wavelength dispersive techniques and ZAF corrections. Analytical precision of major elements (> 2 wt. % oxide) is $\pm 2\%$ relative, and minor element precision is $\pm 8\%$.

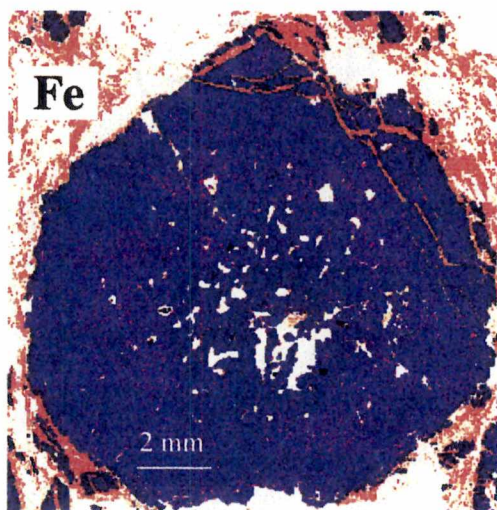
Qualitative x-ray maps were obtained with an accelerating voltage of 15kV, a beam size of 1.0 μm , a beam current of 4.0 nA, and a counting time of 100 milliseconds. X-ray images were collected of 11 elements Ca, Na, Mg, Mn, Fe, Al, Si, S, P, K, and Ti. All quantitative analyses are given in Appendix 4. All qualitative analyses are in Appendices 1-3, and selected qualitative x-ray images are shown in Figures 1.5a-d.

There were three steps in the processing of the qualitative images from the electron microprobe. Step one was the determination of the size of grid that would cover the entire garnet and some of the surrounding matrix. The grid consisted of an $n \times n$ array of x-ray points. The x-ray at these points represented the intensity and the beam diameter and an area around it represented the diameter of the pixel. The size of the raster depended on the amount of time available for counting and the desired resolution of the image. The time needed for the image depended on the size of the garnet and the amount of time spent at each point.

For Sample 1, an array size of 1024×1024 and a pixel size of 15 μm was used. This resulted in 64 arrays of 128×128 , which took too much time and too much computer memory to deal with. For the next two garnets an array of 512×512 and a pixel size of 23 μm was used. This lowered the resolution of the image, but it was much

Figure 1.5 Following Page. All four images are qualitative x-ray maps of Sample 3 that were pieced together in the program Transform. All four images are based on the number of x-ray K_{α} counts. **a)** The Fe x-ray image. **b)** The Mg x-ray image. **c)** The Mn x-ray image. **d)** The Ca x-ray image. The explanation is in the text.

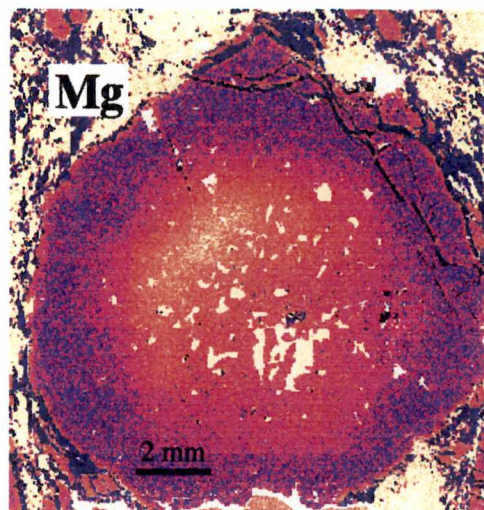
a.)



0 20 40 60 80 100 120 140 160

Counts Fe K_{α}

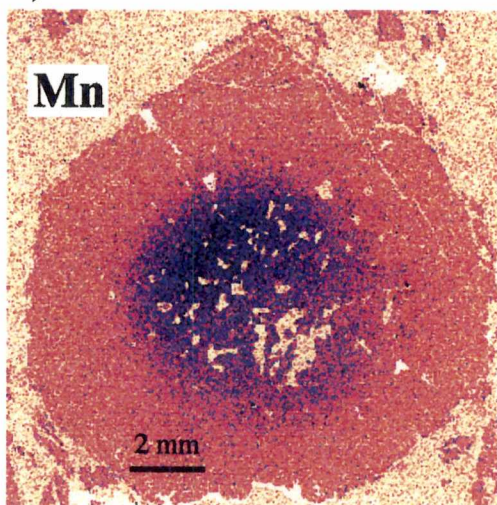
b.)



0 20 41 61 81 102 122 142

Counts Mg K_{α}

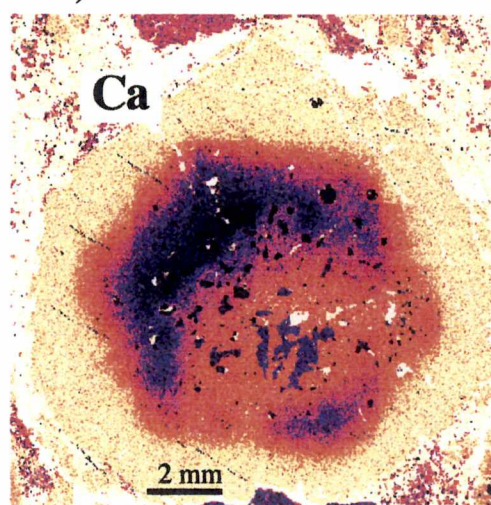
c.)



0 5 10 15 20 25 30 35

Counts Mn K_{α}

d.)



0 10 20 30 40 50 60 70 80 90 100

Counts Ca K_{α}

easier to manipulate the data. This resulted in 64 arrays of 64×64 data points being collected for each garnet.

The arrays were pieced together in the program *Transform PPC 3.4*, and images of the 11 elements were created by assigning a color scale to the range of microprobe counts. Figures 1.5 a, b, c, and d are images of the major cations Fe, Mg, Mn, and Ca for Sample 3. All images can be seen in appendices 1a, 2a, and 3a.

Mineral masks were created to filter out parts of each elemental map according to the number of counts. This mask could then be used to create a maximum and minimum threshold of counts for each element in a particular mineral. Combinations of elemental masks could then be used to partition areas of the thin section for each mineral. Thus, mineral inclusions could be distinguished from the garnet, and the garnet could be distinguished from the matrix. It was also possible to determine different areas of the garnet based on the intensity of calcium zoning within the garnet.

Garnet and plagioclase are examples of the identification of minerals from the elemental masks. Both of these minerals contain a range of counts of Ca and Na. The Ca is a major component of the grossular in the garnet, but the counts for Na are mainly background noise. If one uses a threshold minimum for Na, then it is possible to mask out the entire garnet by multiplying this threshold value times the Na elemental matrix. If the Ca matrix is also multiplied by the value from the Na computation, then the plagioclase mask can be created. It is possible to take the process further and create a semiquantitative plagioclase map based on the number of counts a particular element in the sample relative to the number of counts in the standard analyses.

The entire thin section was reconstructed, but the image could not be used in transform because of the great range in values. Transform codes images from 1-254 and the reconstruction had to be normalized to this number range. This recoding was done with the help of the color program *View 3.03*. The codes for the mineral masks are in Appendices 1d, 2d, and 3d.

II Mineral Assemblages

The dominant assemblage in the samples studied was quartz + biotite + garnet + plagioclase + muscovite + sillimanite + kyanite with minor minerals rutile, ilmenite, K-feldspar, apatite, monazite, and zircon. Staurolite was not observed within the samples studied, but Davidson (1995) and Labotka (personal communication) reported staurolite within samples from the same location.

In thin section the samples are coarse-grained and inequigranular with porphyroblasts of garnet set in a matrix consisting of biotite, muscovite, sillimanite, kyanite, quartz, and plagioclase. Figures 2.1a – c are photomicrographs of the three samples in plain polarized light (top photographs) and crossed polarized light.

The matrix consists of anhedral grains of quartz, anhedral to subhedral grains of muscovite, biotite, and garnet, anhedral grains of feldspar, and subhedral to euhedral sillimanite. There is a dominant foliation defined by the parallel alignment of biotite and sillimanite. This primary foliation is most pronounced near garnet porphyroblasts. There is another foliation defined by prismatic sillimanite, which crosscuts the dominant foliation.

Garnet is the largest of the minerals, and its size ranges from < 1 mm to >1 cm. In thin section, garnet is white to light pink in color. There is a distinct change in color from the pinkish core of the garnet to the clear rim. The garnet grains are subhedral, and there are microfractures, veins, large fractures, and shears within the garnet.

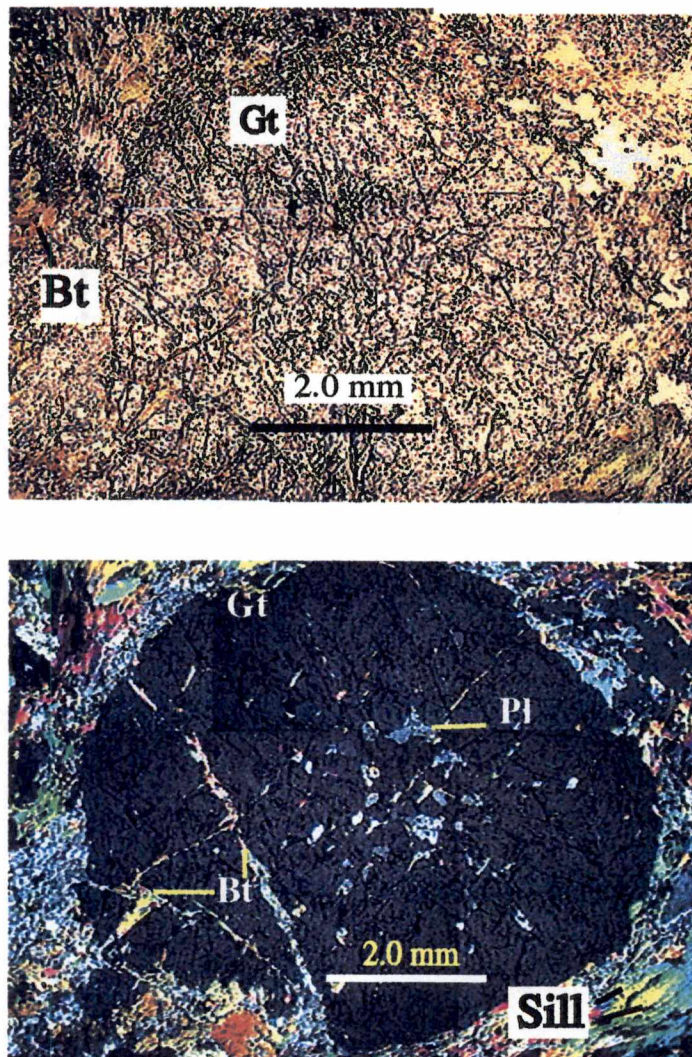


Figure 2.1 Photomicrograph. **a)** Sample 1. The top picture is in plain polarized light (PPL). The bottom image is in crossed polarized light (XPL). Gt=garnet; Bt= biotite; Pl= plagioclase; Sill = sillimanite.

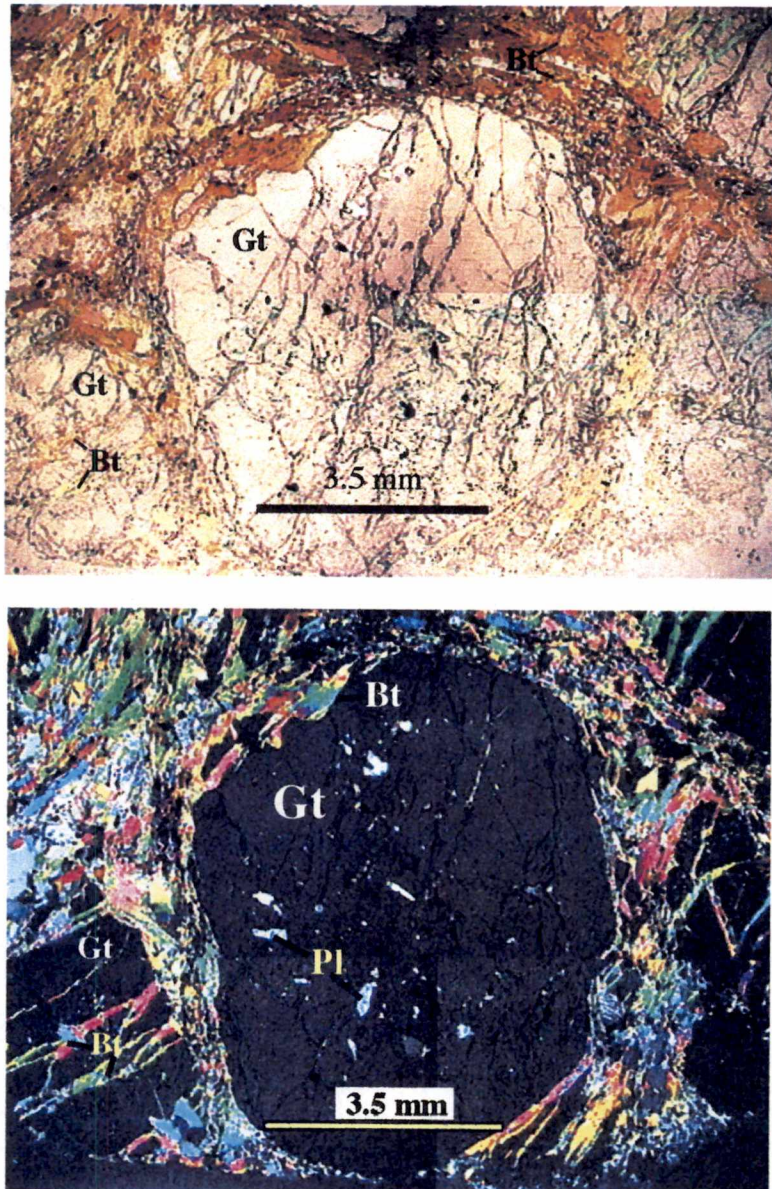


Figure 2.1 (continued) b) Sample 2. The top picture is in plain polarized light. The bottom picture is with crossed polars. Gt = garnet; Pl = plagioclase; Bt = biotite.

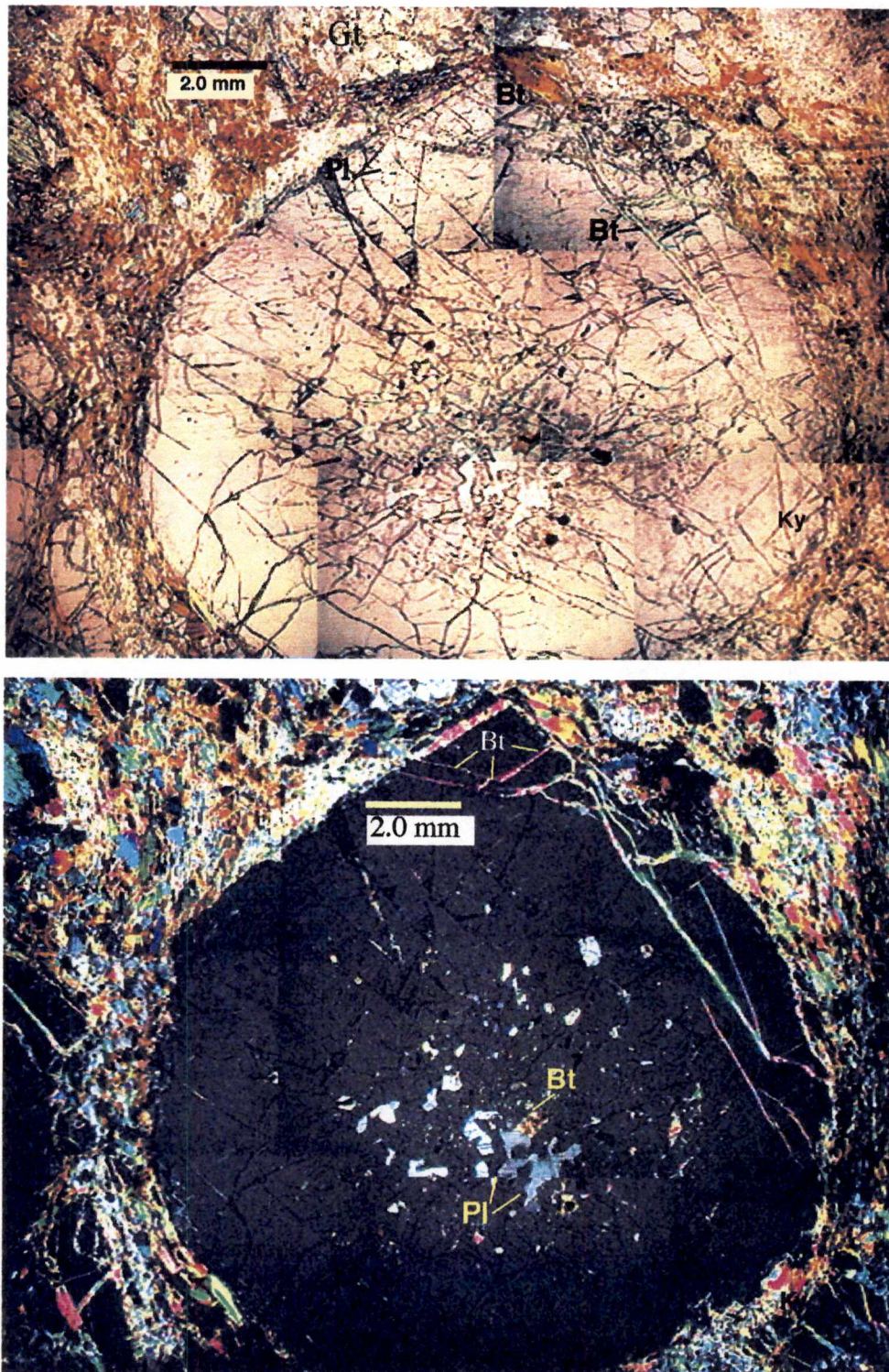


Figure 2.1 (continued) c) Sample 3. The top picture is in plain polarized light and the bottom picture is with crossed polars.

Some parts of the garnet have been broken off and form islands within the matrix.

Fractures within the garnet contain biotite, quartz, plagioclase, and white mica. There are numerous inclusions of biotite, plagioclase, and sillimanite with minor amounts of quartz, muscovite, ilmenite, rutile, apatite, monazite, and K-feldspar within the garnet.

Inclusions of sillimanite needles form patterns that are radial from the center and also tangential to the rim of the garnet. Figure 2.2 is an artistically enhanced photomicrograph of Sample 3. Sample 3 best represents this feature because there is an abundance of sillimanite that is oriented radial from the center of the garnet, and these needles are probably oriented along {111}. The sillimanite inclusions that are tangential to the rim of the garnet are also parallel to the matrix foliation on the opposite side of the garnet rim.

Biotite is subhedral and inequigranular, and (001) faces are in contact with other biotite grains. There is a contrast in color between biotite in the matrix and biotite in the fractures. Matrix biotite is pleochroic in light tan to dark orange brown, while biotite within garnet fractures is pleochroic from clear or light yellow to light green, and there is a change in pleochroism with proximity to the mouth of the fracture. The color of the biotite at the mouth of the fractures is similar to that in the matrix. Matrix biotite can also have undulatory extinction and zircon inclusions within the biotite are common and most of the zircons have halos around their rims. Inclusion biotite is similar in color to the matrix biotite.

Other important minerals within the samples are plagioclase, quartz, sillimanite, kyanite, white mica, rutile, and ilmenite. Plagioclase is anhedral, inequigranular, and locally has albite twinning. A few plagioclase grains have variable extinction angles

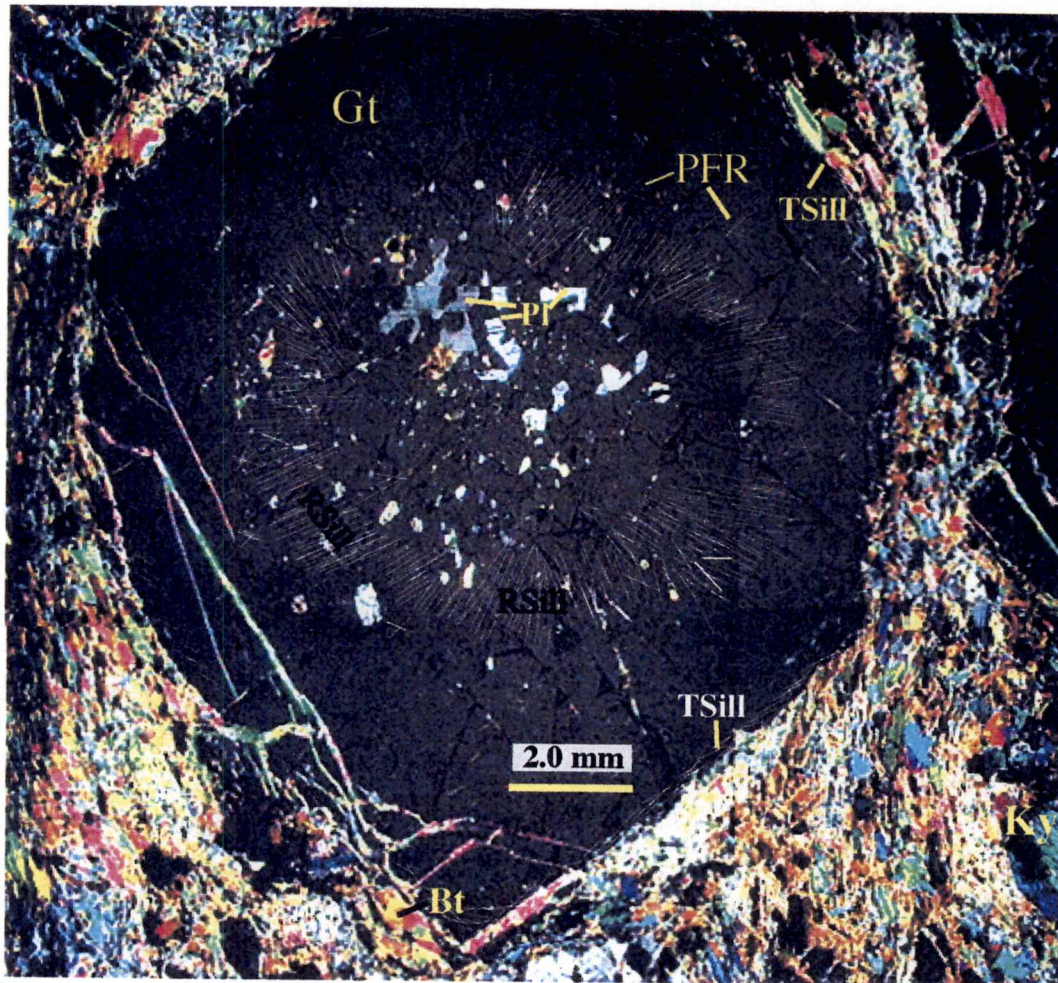


Fig 2.2 Photomicrograph of Sample 3 with artistic enhancement that shows the perpendicular microfractures (PFR), the radial sillimanite (RSill), and the tangential sillimanite (TSill). Gt = garnet; Bt = biotite; Ky = kyanite.

because of compositional zoning, but most plagioclase crystals are not zoned. Quartz is inequigranular and can have undulatory extinction. Most grains have large dihedral angles, which indicates the absence of strain within those quartz grains. Figure 2.3 is a photomicrograph of matrix sillimanite and kyanite taken using crossed polarized light. Sillimanite is present in both prismatic and fibrous forms. Fibrous sillimanite is included within the garnet, but the prismatic sillimanite is euhedral to subhedral and exists within the matrix. Kyanite is kinked, relict and resorbed. Rutile and ilmenite inclusions, within the garnet, are frequently found adjacent to each other. There are anhedral grains of both oxides within the matrix.

Mineral Composition

Representative quantitative electron microprobe analyses of the three samples are presented in Tables 2.1a, b, and c. Table 2.2a shows the range in values for the cations of important minerals, while Table 2.2b gives the garnet endmember ranges and the anorthite range within the plagioclase. All data are in Appendix 5.

Garnet compositions contain weight percentages of $\text{FeO} > \text{MgO} > \text{CaO} > \text{MnO}$, with minor amounts of TiO_2 and Na_2O , and they can be categorized as almandine – pyrope garnets. There are differences in composition between the core and rim of the garnet because of compositional zoning.

Figures 2.4a and 2.4b are bar graphs that show the abundance of the garnet endmembers, almandine, pyrope, grossular, and spessartine, and the diagrams are based on the mole fraction of each endmember. The graphs do not represent a random statistical histogram, but each analysis is reported relative to the rim, core, or fractures of the garnet,

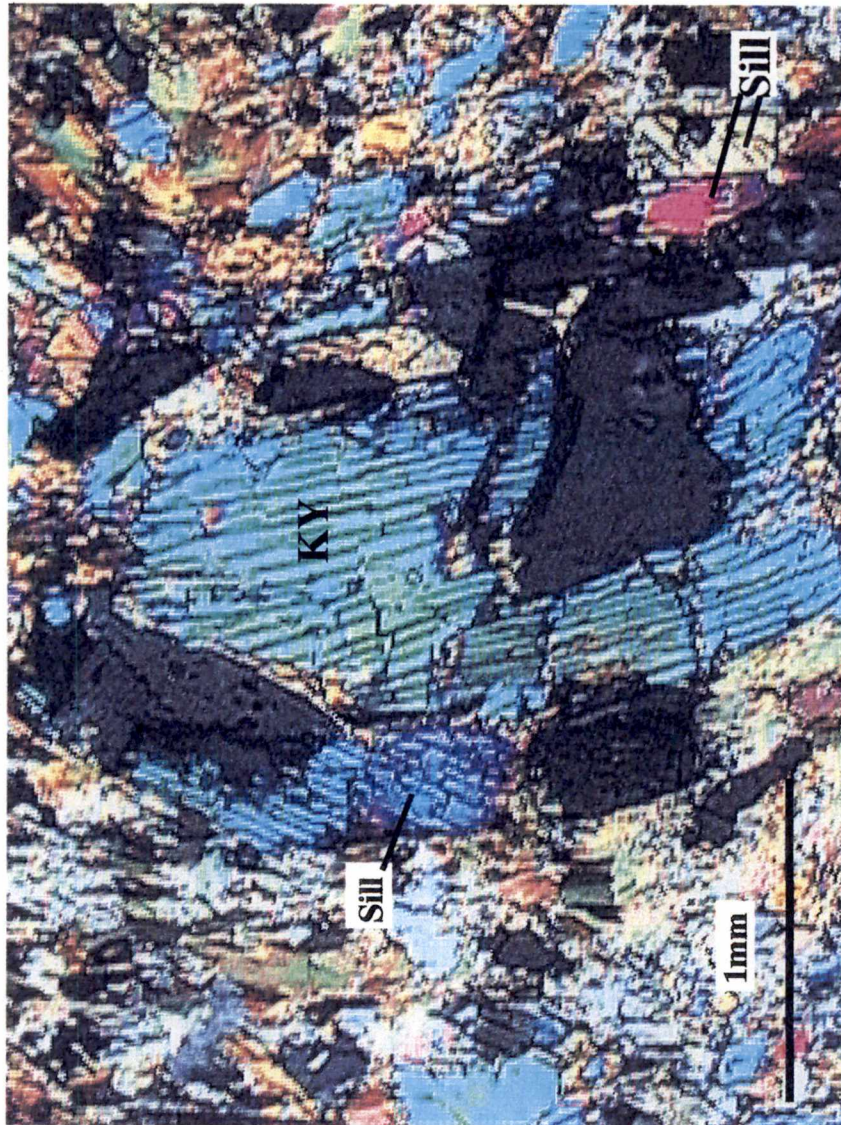


Figure 2.3 Kyanite (Ky) and sillimanite (Sill) in the matrix of Sample 3.

Table 2.1 Mineral Compositions. a) Compositions of selected minerals from Sample 1 for the Cullowhee Gneiss.

Oxide	MINERAL POINT	Garnet 5(R)*	Garnet 11(C)	Biotite 3(M)	Biotite 13(I)	Biotite 72(F)	Plagioclase 83(M)	Plagioclase 53(C)	Muscovite 18(C)
SiO ₂	36.6	38.1	36.6	38.7	36.5	61.2	52.0	46.7	
TiO ₂	0.01	0.03	1.54	1.19	1.22			0.15	
Al ₂ O ₃	21.0	21.6	18.8	18.6	19.0	24.1	30.1	34.2	
Cr ₂ O ₃	0.00	0.01	-----	-----	-----	-----	-----	-----	
MgO	4.45	7.07	13.9	18.9	13.5	-----	-----	1.66	
CaO	1.23	4.41	0.00	0.10	0.05	5.33	12.70	0.01	
MnO	1.48	1.75	0.03	0.04	0.05	-----	-----	0.00	
FeO	32.8	25.5	14.3	8.46	14.20	0.40	0.27	0.87	
Na ₂ O	0.02	0.01	0.35	0.62	0.34	8.53	4.24	0.31	
K ₂ O	-----	-----	9.23	8.43	9.23	0.16	0.02	11.00	
H ₂ O	-----	-----	3.71	3.74	3.69	-----	-----	4.40	
F	-----	-----	0.64	0.93	0.63	-----	-----	0.17	
Cl	-----	-----	0.05	0.02	0.07	-----	-----	0.01	
Total	99.4	99.6	99.1	99.7	98.6	99.7	99.4	99.4	
Formula Proportions									
Si	2.95	2.97	5.46	5.54	5.47	2.73	2.38	6.24	
Ti	0.00	0.00	0.17	0.13	0.14	-----	-----	0.02	
Al	1.99	1.99	3.30	3.15	3.36	1.27	1.62	5.39	
Cr	0.00	0.00	-----	0.00	0.00	-----	-----	-----	
Mg	0.53	0.82	3.08	4.05	3.02	-----	-----	0.33	
Ca	0.11	0.37	0.00	0.02	0.01	0.26	0.62	0.00	
Mn	0.10	0.12	0.00	0.01	0.01	-----	-----	0.00	
Fe	2.21	1.66	1.79	1.01	1.78	0.02	0.01	0.10	
Na	0.00	0.00	0.10	0.17	0.10	0.74	0.38	0.08	
K	-----	-----	1.76	1.54	1.76	0.01	0.00	1.87	
H	-----	-----	3.69	3.58	3.69	-----	-----	3.93	
F	-----	-----	0.30	0.42	0.30	-----	-----	0.07	
Cl	-----	-----	0.01	0.00	0.02	-----	-----	0.00	
Total	8.00	8.00	15.6	15.6	15.6	5.01	5.00	14.0	

* R = Rim composition, C = Core composition, F = Fracture composition, M = Matrix composition

I = Inclusion; ----- = Not Determined; All Fe reported as Fe²⁺.

TABLE 2.1 (continued) b) Compositions of selected minerals from Sample 2.

Oxide	MINERAL POINT	Garnet 1(R)*	Garnet 48(C)	Biotite 3(M)	Biotite 80(M)	Plagioclase 134 (M)	Plagioclase 181(I)	Muscovite 184(M)	Ilmenite 144(I-R)	Ilmenite 165(I-C)
SiO ₂	37.3	37.3	37.3	36.6	35.6	62.0	46.1	46.4	0.02	0.02
TiO ₂	0.02	0.02	0.12	0.68	1.21	----	----	0.37	53.0	52.9
Al ₂ O ₃	21.5	21.5	21.2	19.8	19.3	23.4	34.4	33.2	0.01	0.01
Cr ₂ O ₃	0.00	0.00	0.00	----	----	----	----	----	0.02	0.06
MgO	4.93	4.93	3.13	15.2	13.4	----	----	1.39	1.91	1.53
CaO	1.17	1.17	9.29	0.07	0.02	4.91	17.90	0.10	0.01	0.01
MnO	1.33	1.33	5.12	0.00	0.00	----	----	0.02	0.19	1.49
FeO	32.9	32.9	22.0	12.1	14.7	0.01	0.27	1.05	44.0	43.2
Na ₂ O	0.01	0.01	0.00	0.33	0.29	8.92	1.39	0.95	0.02	0.03
K ₂ O	-----	-----	-----	9.24	9.57	0.10	0.09	9.92	-----	-----
H ₂ O	-----	-----	-----	3.74	3.76	-----	-----	4.41	-----	-----
F	-----	-----	-----	0.59	0.40	-----	-----	0.02	-----	-----
Cl	-----	-----	-----	0.05	0.08	-----	-----	0.00	-----	-----
Total	99.4	99.4	99.0	98.3	98.3	99.4	100.2	97.8	99.3	99.4
Formula Proportions										
Si	2.98	2.98	2.97	5.44	5.37	2.77	2.12	6.29	0.00	0.00
Ti	0.00	0.00	0.01	0.08	0.14	-----	-----	0.04	4.00	3.99
Al	2.02	2.02	1.99	3.46	3.43	1.23	1.87	5.30	0.00	0.00
Cr	0.00	0.00	0.00	-----	-----	-----	-----	-----	0.00	0.00
Mg	0.59	0.59	0.37	3.36	3.01	-----	-----	0.28	0.29	0.23
Ca	0.10	0.10	0.79	0.01	0.00	0.23	0.88	0.01	0.00	0.00
Mn	0.09	0.09	0.35	0.00	0.00	-----	-----	0.00	0.02	0.13
Fe	2.20	2.20	1.47	1.50	1.86	0.00	0.01	0.12	3.69	3.63
Na	0.00	0.00	0.00	0.09	0.09	0.77	0.12	0.25	0.00	0.01
K	-----	-----	-----	1.75	1.84	0.01	0.01	1.72	-----	-----
H	-----	-----	-----	3.71	3.79	-----	-----	3.99	-----	-----
F	-----	-----	-----	0.28	0.19	-----	-----	0.01	-----	-----
Cl	-----	-----	-----	0.01	0.02	-----	-----	0.00	-----	-----
Total	8.00	8.00	8.00	15.7	15.7	5.01	5.01	14.0	8.00	8.00

* R = Rim Composition, C = Core composition, F = Fracture composition, M = Matrix composition,

I = Inclusion, I-R = Inclusion @ the rim, I-C = Inclusion @ the Core; all Fe reported as Fe²⁺; ---- = Not Determined.

Table 2.1 (continued) e) Compositions of selected minerals from Sample 3.

Oxide	MINERAL POINT	Garnet 22(R)*	Garnet 26(C)	Biotite 10(M)	Biotite 192(I)	Biotite 233(F)	Plagioclase 23(M)	Plagioclase 264(I)	Ilmenite 38(I)	K-feldspar 172b(I)
SiO ₂	37.5	37.5	37.5	36.2	39.3	37.2	62.0	51.1	0.03	64.2
TiO ₂	0.00	0.00	0.06	0.85	1.41	0.00	----	----	52.4	----
Al ₂ O ₃	21.6	21.6	21.5	19.1	18.4	20.0	23.7	30.8	0.02	18.6
Cr ₂ O ₃	0.04	0.04	0.01	0.00	0.00	0.01	----	----	0.03	----
MgO	4.94	4.94	6.05	13.9	19.7	16.1	----	----	0.97	----
CaO	1.37	1.37	6.14	0.01	0.00	0.03	4.85	13.9	0.04	0.25
MnO	1.36	1.36	1.93	0.08	0.00	0.03	----	----	0.67	----
FeO	32.7	32.7	24.2	14.2	7.35	11.7	0.16	0.34	44.7	0.13
Na ₂ O	0.04	0.04	0.02	0.33	0.47	0.37	9.00	3.83	0.00	1.15
K ₂ O	----	----	----	9.67	8.91	9.40	0.08	0.06	----	15.0
H ₂ O	----	----	----	3.60	4.22	3.99	----	----	----	----
F	----	----	----	0.77	0.00	0.19	----	----	----	----
Cl	----	----	----	0.10	0.01	0.04	----	----	----	----
Total	100.5	100.5	99.2	98.8	99.8	99.0	99.7	100.1	99.1	99.4

Formula Proportions										
Si	2.97	2.97	2.95	5.43	5.58	5.46	2.76	2.33	0.00	2.98
Ti	0.00	0.00	0.00	0.10	0.15	0.00	----	----	3.99	----
Al	2.01	2.01	1.99	3.38	3.08	3.45	1.24	1.65	0.00	1.02
Cr	0.00	0.00	0.00	----	0.00	0.00	----	----	0.00	----
Mg	0.58	0.58	0.71	3.10	4.17	3.53	----	----	0.15	----
Ca	0.12	0.12	0.52	0.00	0.00	0.00	0.23	0.68	0.00	0.01
Mn	0.09	0.09	0.13	0.01	0.00	0.00	----	----	0.06	----
Fe2+	2.17	2.17	1.59	1.79	0.87	1.43	0.01	0.01	3.78	0.01
Na	0.01	0.01	0.00	0.09	0.13	0.11	0.78	0.34	0.00	0.10
K	----	----	----	1.85	1.61	1.76	0.00	0.00	----	0.89
H	----	----	----	3.61	----	----	----	----	----	----
F	----	----	----	0.37	----	----	----	----	----	----
Cl	----	----	----	0.03	----	----	----	----	----	----
Total	8.00	8.00	8.00	15.8	15.6	15.8	5.01	5.02	8.00	5.01

R = Rim composition, C = Core composition, F= Fracture composition, M = matrix composition

I = Inclusion; All Fe reported as Fe²⁺; ---- = Not Determined.

Table 2.2 Range of formula proportions in the Cullowhee Gneiss. (a) Biotite, muscovite, and ilmenite.

Mineral	Si	[⁶] Al	[⁴] Al	Ti	Fe ²⁺	Mg	Mn
Biotite(M)	2.67 - 2.75	0.34 - 0.55	1.26 - 1.33	0.00 - 0.10	0.75 - 0.97	1.38 - 1.69	0.00 - 0.01
Biotite(I)	2.71 - 2.94	0.29 - 0.41	1.06 - 1.29	0.05 - 0.10	0.42 - 0.57	1.78 - 2.12	0.00 - 0.01
Biotite(F)	2.59 - 2.82	0.26 - 0.50	1.18 - 1.41	0.00 - 0.16	0.65 - 1.31	1.36 - 1.78	0.00 - 0.03
Muscovite	3.10 - 3.13	-----	-----	0.01 - 0.04	0.06	0.13 - 0.14	-----
Ilmenite	-----	-----	-----	0.99 - 1.00	0.89 - 0.95	0.03 - 0.07	0.03

Mineral	Ca	Na	K	Fe/Fe+Mg	□	Na/Na+K
Biotite(M)	0.00 - 0.02	0.04 - 0.07	0.74 - 0.94	0.31 - 0.41	0.01 - 0.21	0.04 - 0.07
Biotite(I)	0.00 - 0.01	0.02 - 0.09	0.75 - 0.95	0.17 - 0.28	0.03 - 0.18	0.02 - 0.10
Biotite(F)	0.00 - 0.04	0.01 - 0.06	0.63 - 0.92	0.27 - 0.49	0.03 - 0.30	0.01 - 0.07
Muscovite	0.00 - 0.01	0.08 - 0.13	0.77 - 0.87	0.30 - 0.32	-----	0.09 - 0.13
Ilmenite	-----	-----	-----	0.93 - 0.97	-----	-----

(b) Range of components for garnet and plagioclase in the Cullowhee Gneiss.

Mineral	X _{Grossular}	X _{Pyrope}	X _{Spessartine}	X _{Almandine}	X _{Anorthite}
Garnet	0.00 - 0.27	0.12 - 0.39	0.01 - 0.13	0.49 - 0.80	-----
Plagioclase	-----	-----	-----	-----	0.10 - 0.88

Notes: X = Mole Fraction; □ = Intersite Vacancy; M = Matrix; I = Inclusion; F = Fracture; ----- = Not Determined

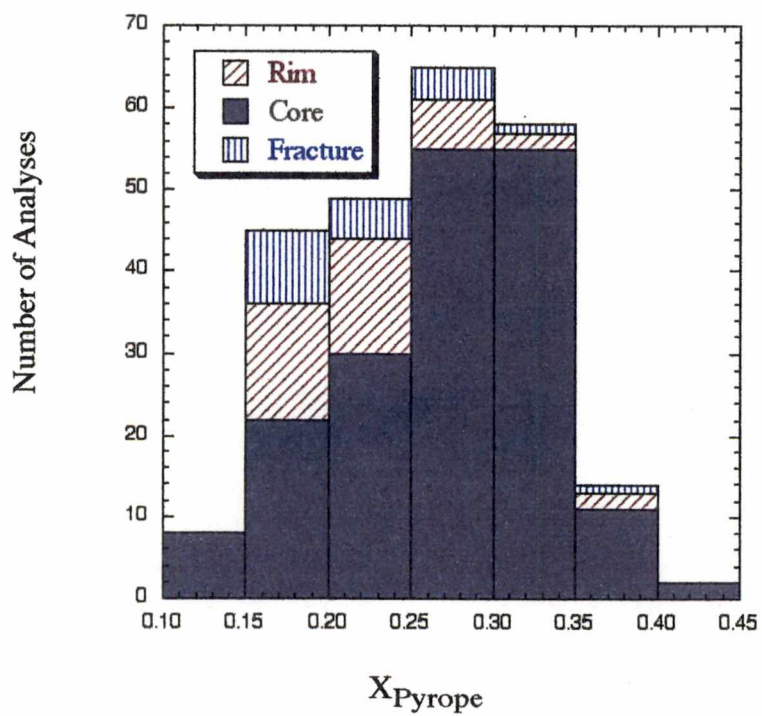
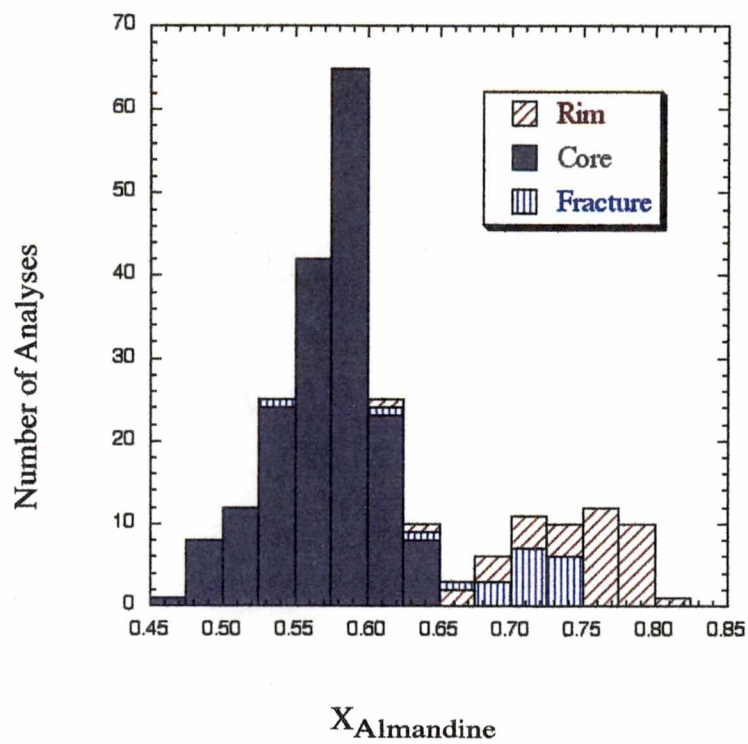


Figure 2.4 Histogram of the mole fraction. **a)** Almandine and pyrope in the core, rim, and at the fracture boundaries for all garnet analyses.

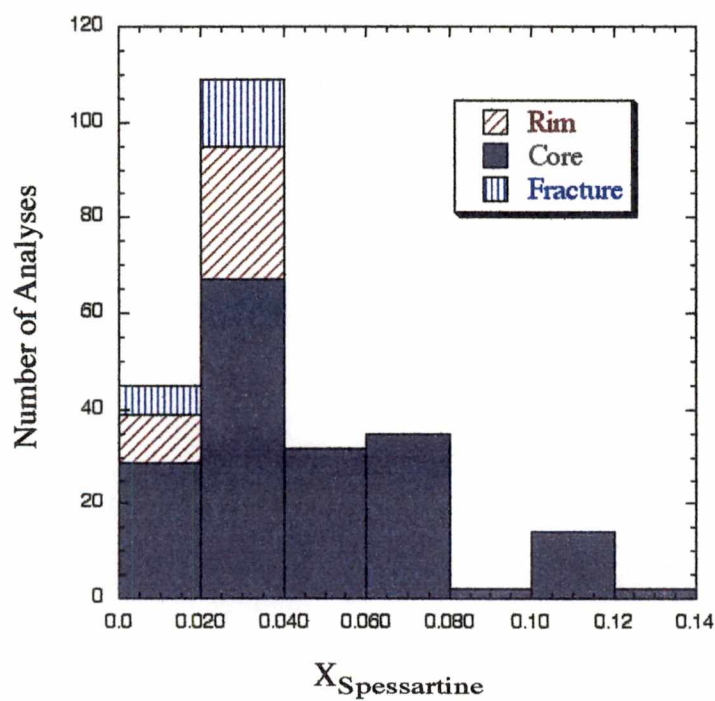
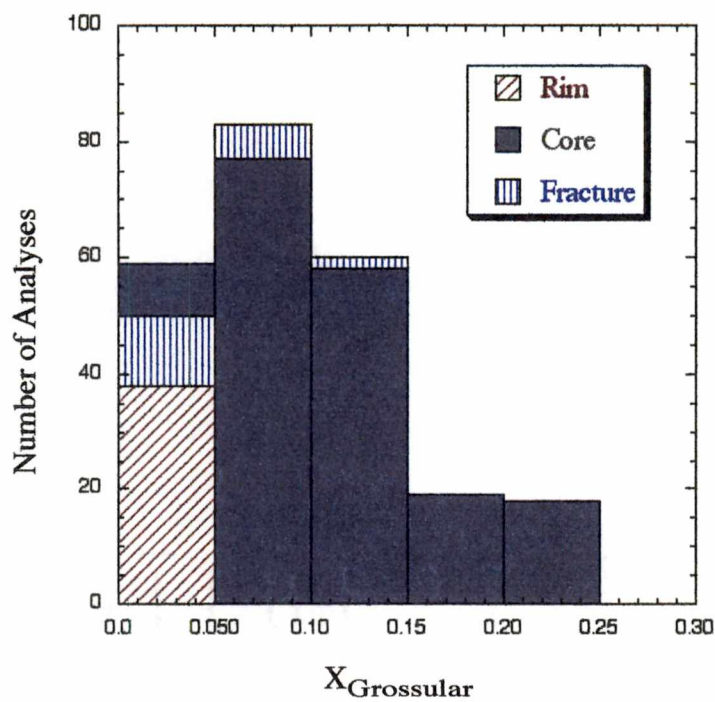


Figure 2.4 (continued) b) Histogram of the mole fraction of grossular and spessartine in the core, rim, and at the fracture boundaries for all garnet analyses.

and there are differences between the core and rim values. The ranges of values for grossular and spessartine indicate that a majority of analyses containing a higher mole fraction of these two endmembers are in the core of the garnet. The core also has a wider range of values than the rim. Almandine, on the other hand, is lower in the core than in the rim and the fractures, and the range of values is approximately the same. Pyrope is lower in the rim and fractures than in the core.

Figures 2.5a - 2.5c show the range in garnet composition for the three samples studied. The locations of the analyses are shown by the arrows that connect them to a particular region of the garnet on the accompanying micrograph. The micrographs were constructed from x-ray images and are discussed in the next chapter. The corners of the diagram are the garnet end-members grossular, almandine, and pyrope and the original mole fraction values were normalized to fit on the ternary. The height of the small triangles represents the amount of spessartine within the analysis.

The three diagrams show similar trends concerning the endmembers grossular and spessartine, which are at the maximum in the cores of the garnets. The ternary diagram in Figure 2.5a (Sample 1) does not indicate any trend for almandine and pyrope, but there appears to be an increase in the pyrope content in the interior of the garnet of Sample 3. Sample 2 (Figure 2.5b) has a well-defined trend for almandine and pyrope. The reason why the trend for this sample is more defined than the others will become clearer in chapter three. For Sample 2, the spessartine and grossular had maximum values in the core of the garnet, while the garnet became enriched in almandine during the later stages of growth. The highest grossular content doesn't coincide with the maximum

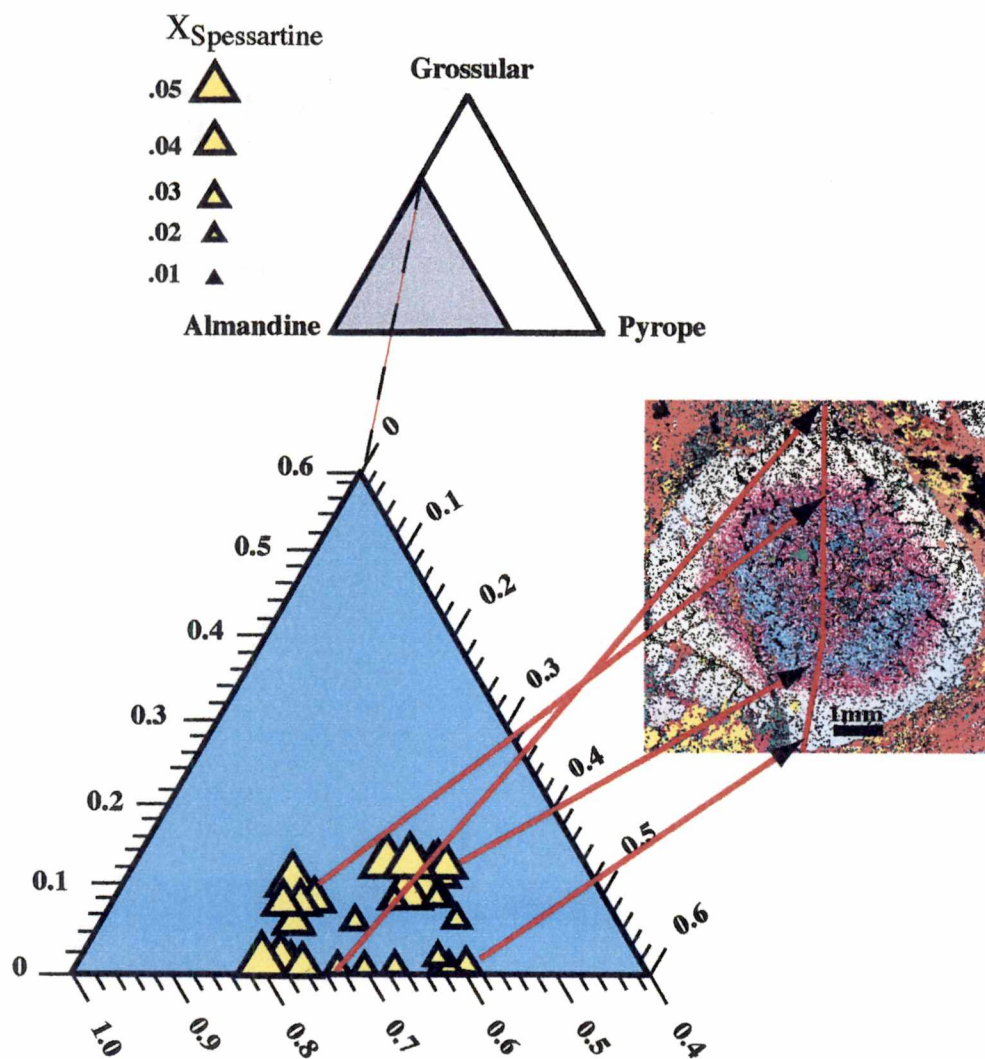


Figure 2.5 Garnet ternary diagram. a) The differences between the rim and the core quantitative values for the end-members grossular, pyrope, almandine, and spessartine along the traverse of Sample 1. The arrows indicate the approximate location on the micrograph where the analyses were taken.

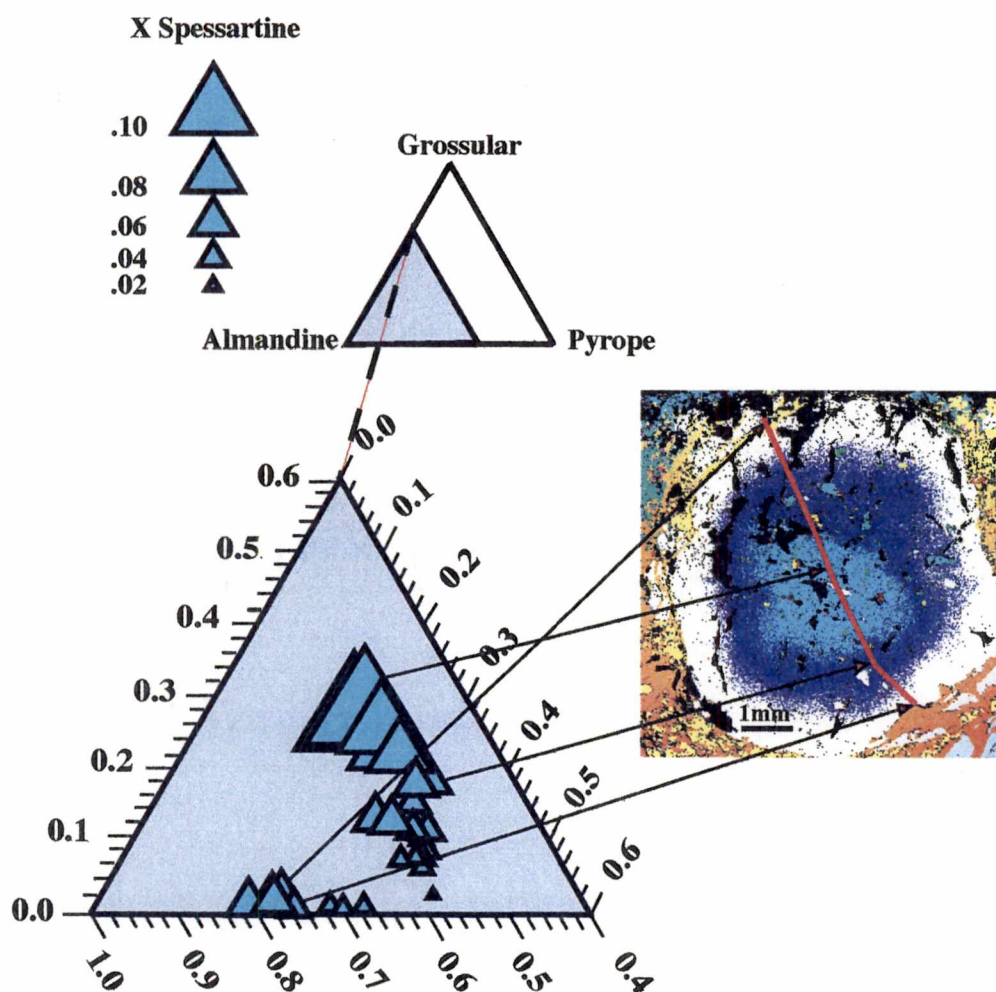


Figure 2.5 (continued) b) Garnet ternary diagram showing the differences between the rim and the core quantitative values for the end-members grossular, pyrope, almandine, and spessartine along the traverse of Sample 2.

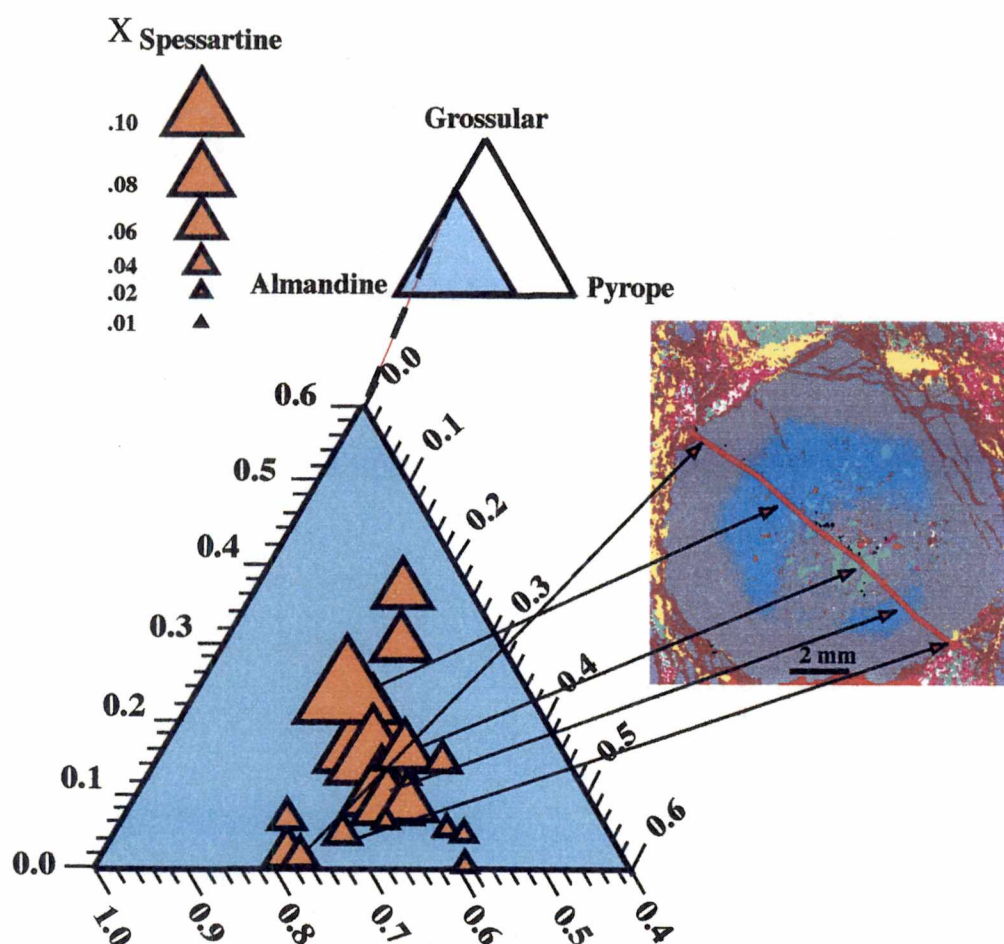


Figure 2.5 (continued) c) Garnet ternary diagram showing the differences between the rim and the core quantitative values for the end-members grossular, pyrope, almandine, and spessartine along the traverse of Sample 3.

pyrope content.

Biotite compositions reflect differences in textures between matrix, inclusion, and biotite within the fractures of the garnet. Table 2.2a lists the range of formula proportion values for matrix, inclusion, and fracture biotite. Biotite analyses from the fractures are similar to those from the matrix. The fracture biotite contains a greater range for the iron and magnesium cations than the matrix biotite, and this small disparity is also reflected in the range of the $\text{Fe}/(\text{Fe} + \text{Mg})$. There is a distinction between the matrix and fracture biotite and the biotite that is included in the garnet. The $\text{Fe}/(\text{Fe} + \text{Mg})$ values for matrix and fracture biotite are 0.27 - 0.49, while the $\text{Fe}/(\text{Fe} + \text{Mg})$ for biotite included within the garnet are 0.17 - 0.28. The $\text{Fe}/(\text{Fe} + \text{Mg})$ of biotite in the fractures is similar to the $\text{Fe}/(\text{Fe} + \text{Mg})$ of biotite in the matrix. The chemical distinction between the green biotite of the fractures and the brown biotite of the matrix and the inclusions in the garnet is not ascertained. Guidotti (1977) and Robinson (1991) observed a direct correlation between Ti and the $\text{Fe}/(\text{Fe} + \text{Mg})$ of biotite, but there is no clear relation in the analyses plotted in Figure 2.6. Figure 2.6 does show a distinction between the $\text{Fe}/(\text{Fe} + \text{Mg})$ values of the core versus those of the matrix and the fractures. Figure 2.7 indicates that there is a higher percentage of ^{6}Al to ^{4}Al in most of the samples, and most plot above the ideal tschermak substitution line. It is also evident that the majority of the inclusion samples contain less ^{6}Al and ^{4}Al than the matrix and fracture samples. Na + K cation sums are less than one for all biotite analyses, and this might indicate that there are vacancies in the interlayer cation sites. There is a difference in the Na + K values between the inclusion versus the matrix, and the fracture biotite. Figure 2.8 is a plot of

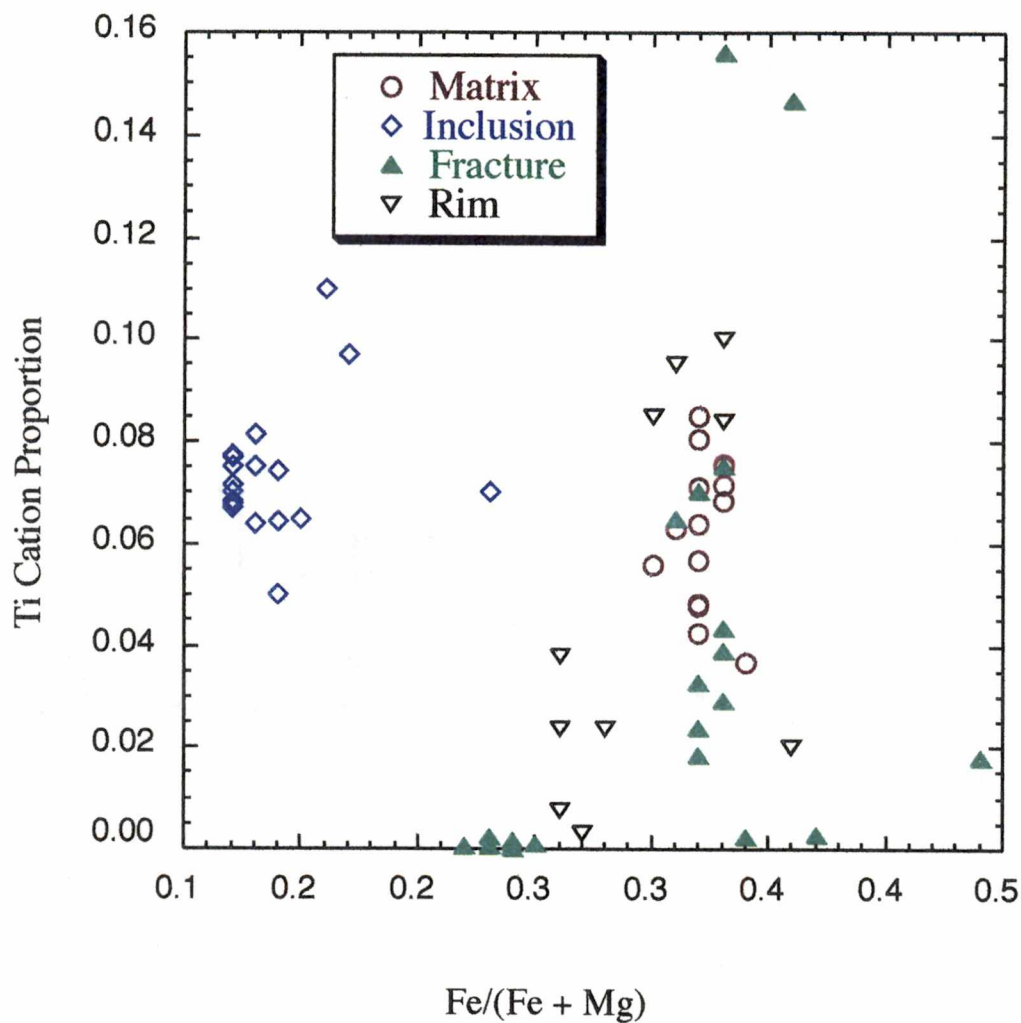
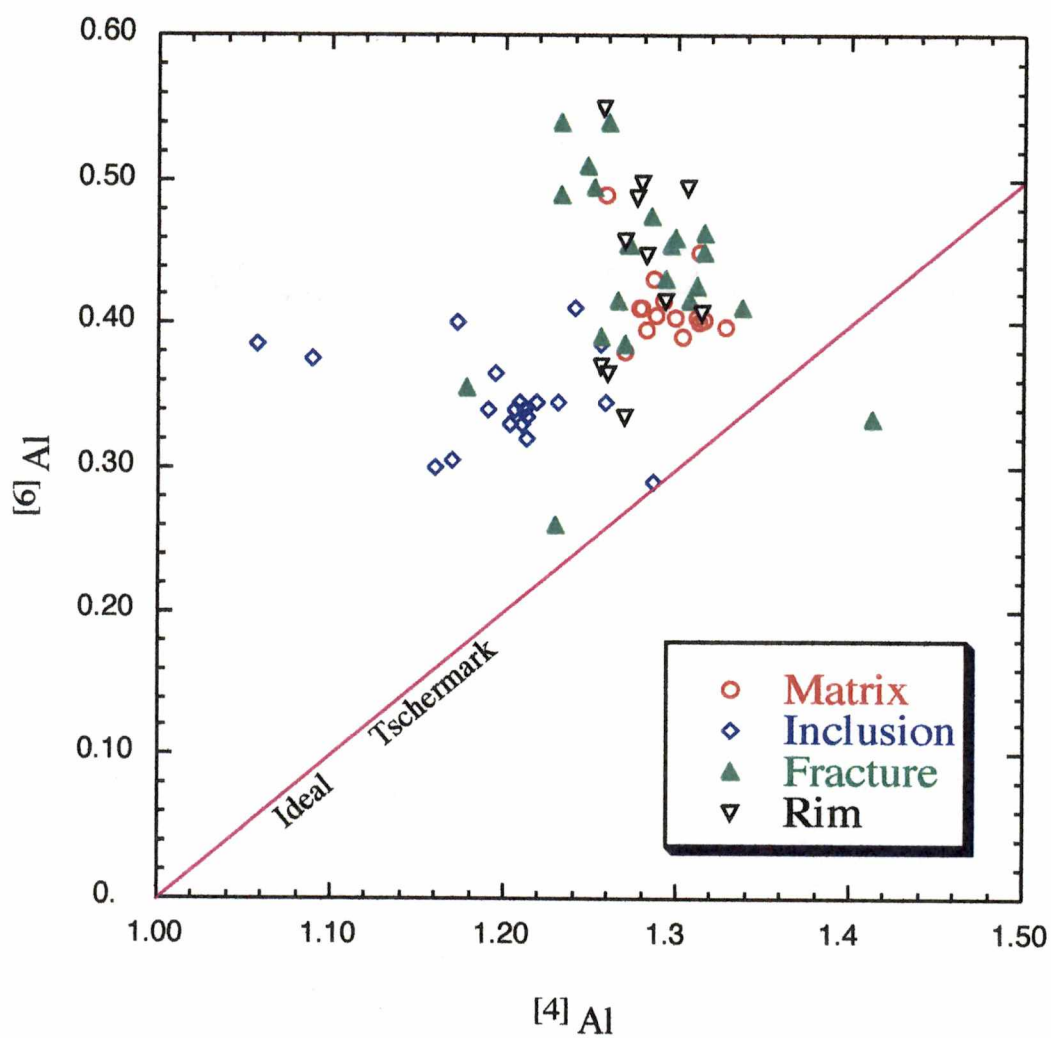


Figure 2.6 Biotite Fe/(Fe + Mg) vs titanium cation proportion for all biotite analyses. Mineral inclusions have a lower Fe/(Fe + Mg) ratio than the analyses from the matrix and fractures.



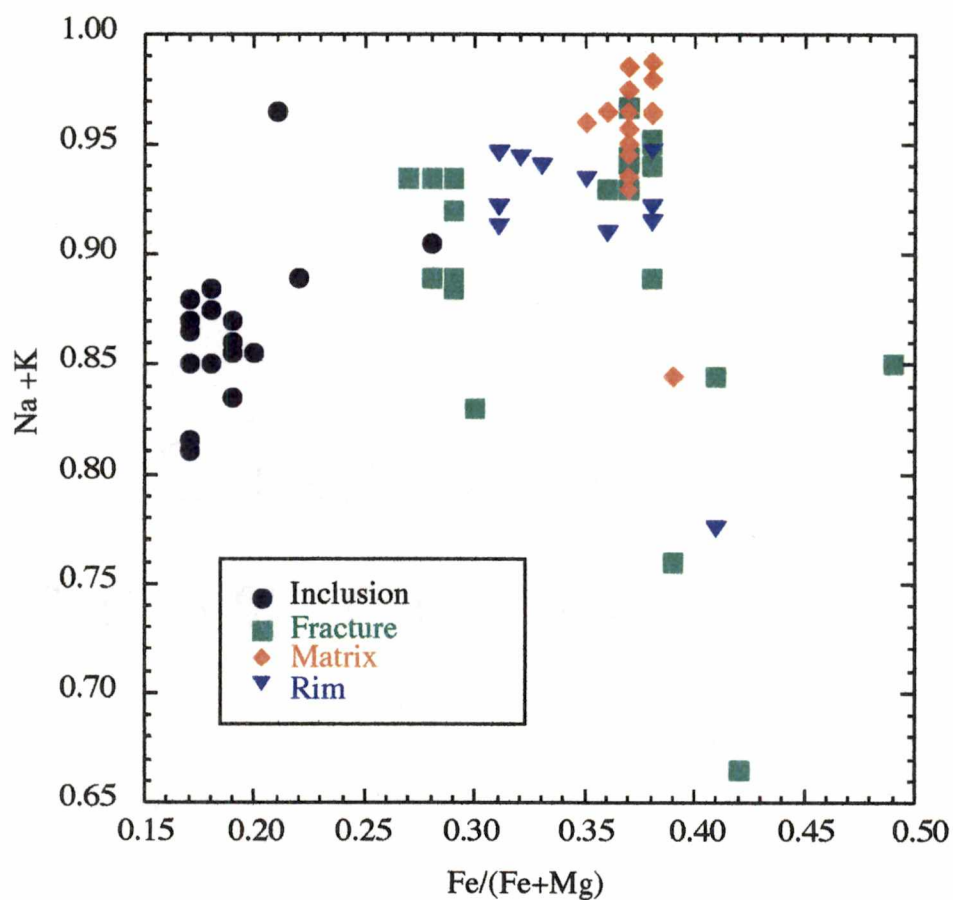


Figure 2.8 The $\text{Fe}/(\text{Fe} + \text{Mg})$ vs $\text{Na} + \text{K}$ values for the biotite analyses in the matrix, core, rim and in the fractures for the samples of this study.

the Fe/(Fe + Mg) in biotite versus Na + K. The inclusion biotite has lower Na + K and Fe/(Fe + Mg) values than the matrix and the fracture biotite, but the error range is large.

Plagioclase has a range in composition (Table 2.2b) from An₁₀ – An₈₈. There is a distinction in composition between the plagioclase inclusions and matrix plagioclase. Figure 2.9 is a plot of grossular versus anorthite content of the coexisting plagioclase, and it shows the distinction between matrix and core plagioclase. Plagioclase in the matrix has a range of An₂₂ - An₃₀, whereas plagioclase inclusions have values from An₃₀ to An₇₀, with one extreme value at An₈₈. There is a strong correlation between the grossular content in the garnet and the anorthite content of plagioclase irrespective of the position in the garnet. The grossular content increases with an increase in anorthite, which indicates that the bulk rock composition controlled the amount of Ca that was partitioned into the plagioclase and garnet during growth.

Potassium feldspar is rare, but a few large grains were identified as inclusions in Sample 3. Orthoclase ranges from 81.1 – 91.2 % and the albite range is 7.7 – 18.5 %. The remaining proportion is filled with anorthite and the range is 0.17 – 1.22 %.

Although muscovite is less abundant than biotite, it is an important mineral inclusion because it and K-feldspar define the second sillimanite isograd. Muscovite was identified in the matrix and as inclusions within the garnet. There is a significant amount of Mg substitution on the octahedral sites, 0.13 – 0.14 formula proportions. There is little Ti, 0.01 – 0.04, and the Na/(Na + K) range is 0.09 - 0.13. The Fe/(Fe + Mg) range for muscovite is 0.30 - 0.32. Two important titanium oxides within the Cullowhee Gneiss are rutile and ilmenite. Rutile is found in the matrix and as inclusions in the garnet.

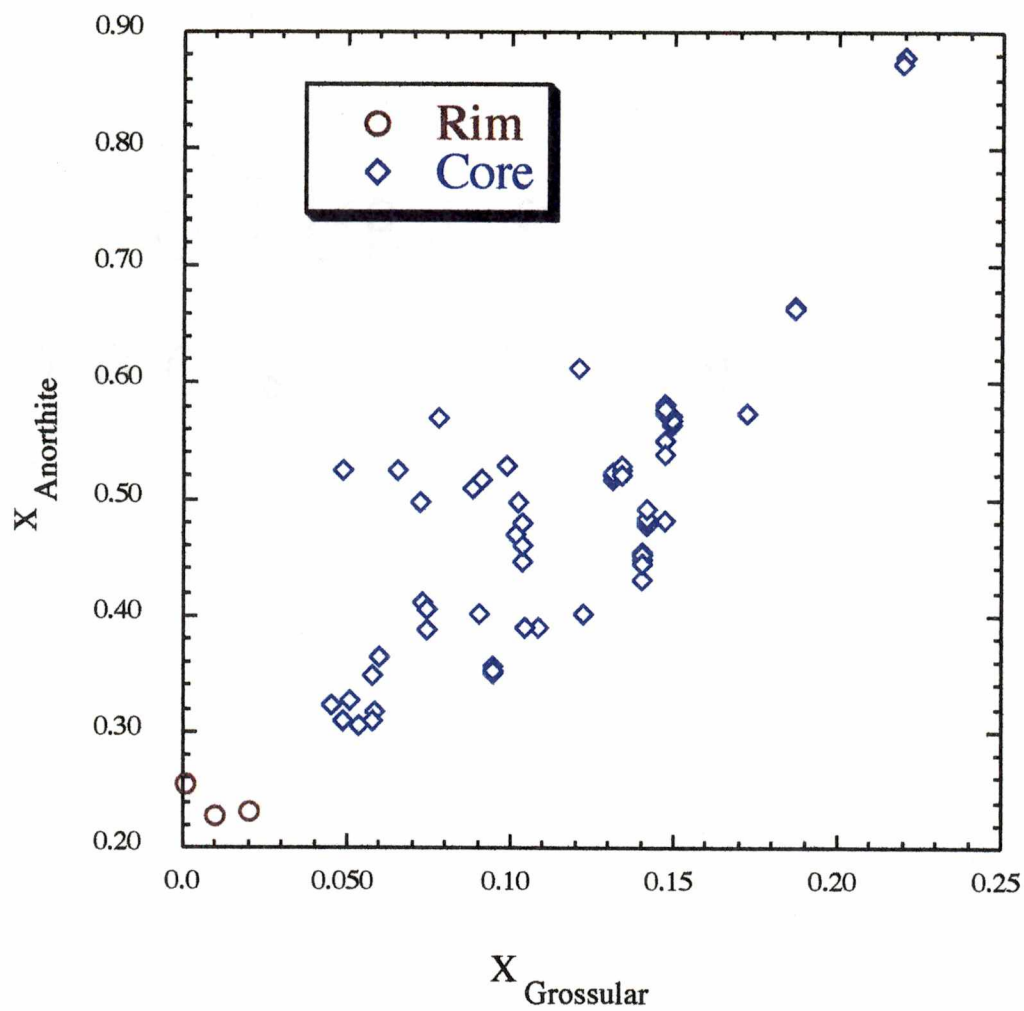
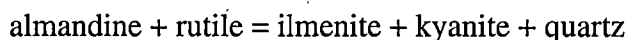


Figure 2.9 Mole fraction grossular vs the mole fraction anorthite in garnet and plagioclase pairs. The data are taken from the inclusion and matrix values for the samples studied.

Rutile is nearly pure TiO_2 with trace amounts of the cations Fe^{2+} , Al, Ca, and Si. The presence of rutile is significant because it is the high-pressure phase in the equation



and it is used to distinguish between lower pressure assemblages in the kyanite field.

Ilmenite inclusions within Samples 2 and 3 contain an average value of 52.8 wt % TiO_2 , 44.0 wt % FeO, with trace amounts of MgO (0.89– 1.9 wt %), and MnO (0.49-1.52 wt %). The juxtaposition of ilmenite and rutile in the garnet indicates that the pressure and the temperature conditions crossed the stability field for muscovite + garnet + rutile during the garnet's growth.

AFM Phases

The silicate phases within the Cullowhee Gneiss can be described in terms of the oxides SiO_2 - Al_2O_3 -FeO- K_2O -MgO- H_2O in the KFMASH system. Mineral assemblages projected from muscovite onto the plane Al_2O_3 -FeO-MgO are shown in Figure 2.10. The AFM diagrams represent the stability fields of a particular metamorphic mineral assemblage and reflect the bulk composition, the pressure, and temperature conditions at the time of mineral formation. The kind of fields connecting the phases in a particular mineral assemblage depends on the variance of the system. Figure 2.10 is the AFM graphical representation for the assemblage aluminum silicate + garnet + biotite, with additional quartz, muscovite, ilmenite, and H_2O projected through muscovite. K-feldspar is plotted at negative infinity. Garnet, biotite, and aluminum silicate make up the three-phase triangle on the diagram, with aluminum silicate at the apex, garnet inside the AFM plane, and biotite plotted below the F – M join.

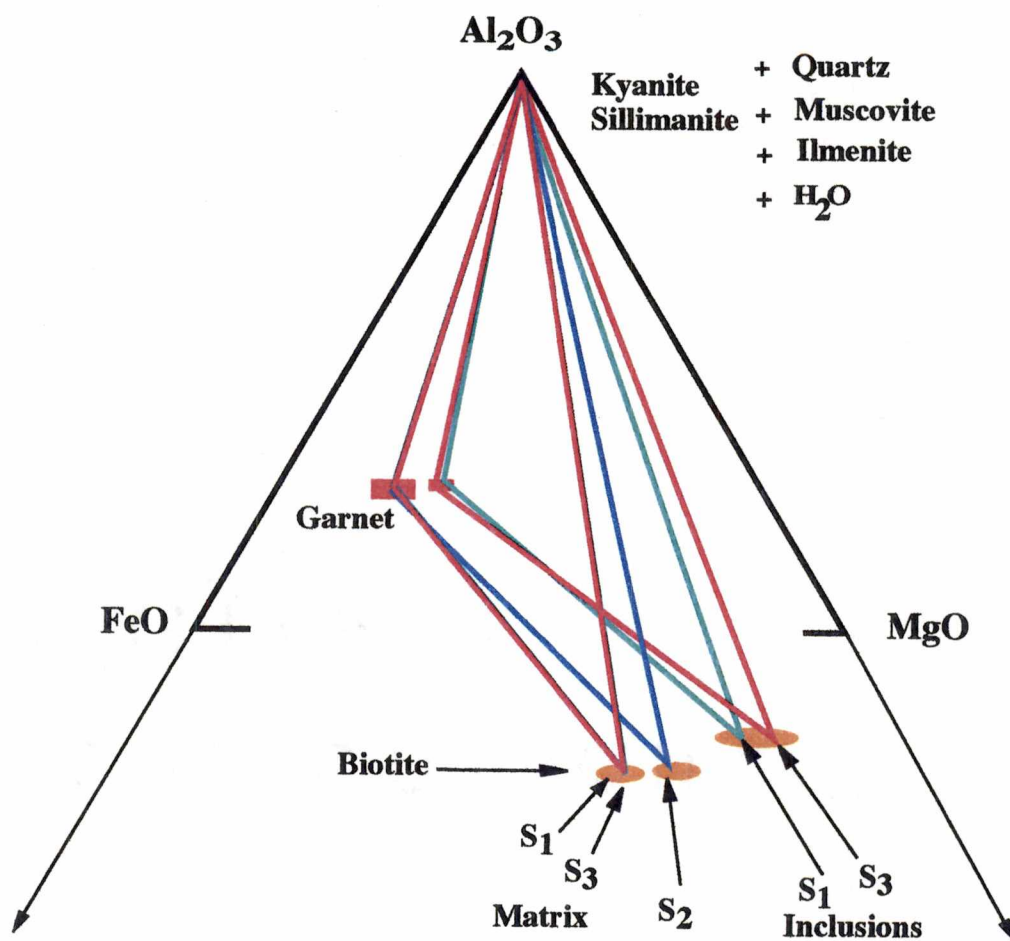


Figure 2.10 Thompson AFM diagram for the samples studied.

— = S₁ = Sample 1; — = S₂ = Sample 2; — = S₃ = Sample 3;
 $\blacksquare$ = Garnet; $\bullet$ = Biotite.

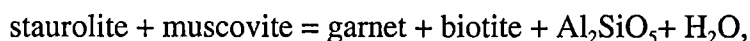
The samples plotted on Figure 2.10 indicate that there are differences between the garnet and biotite rim and core compositions in the samples studied. Garnet core compositions are higher in Mg than the rim concentrations and biotite inclusions have a greater Mg/Fe ratio than the matrix biotite. The biotite inclusions from Sample 1 and Sample 3 have a higher MgO content than the MgO in the biotite from the matrix. Sample 2 has matrix biotite MgO values that are slightly greater than Samples 1 and 2.

The three-phase divariant field represented by the triangles in Figure 2.10 shifts toward the MgO portion of the AFM triangle with an increase in temperature (Tracy, 1976; Robinson, 1991; Thompson, 1957). There are crossing tie lines, which indicates that there was a range in temperature and pressure conditions during metamorphism. The triangles indicate that, for the samples of this study, the metamorphic conditions represented by the core compositions were greater than the conditions for the rim. The stability field of the triangles made by the phases garnet, aluminum silicate, and biotite is located above the staurolite and sillimanite isograds, and the position of the three-phase field is similar to the one shown by Spear (1995) for the muscovite breakdown reaction. There is a greater abundance of MgO within the core of the garnet in this study than in the examples given by Spear, and the position of the samples, for this study, are shifted towards the M portion of the AFM diagram.

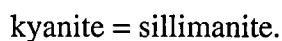
The reaction that defines the breakdown of staurolite to kyanite in the KFMASH system is



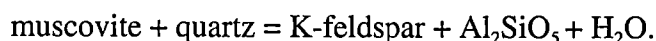
The three phase field made of chlorite + biotite + kyanite shifts towards the Mg part of the AFM triangle with an increase in the temperature. The samples of this study do not contain any staurolite or chlorite, but they do have relict kyanite surrounded by euhedral to subhedral sillimanite. Another equation that causes the breakdown of staurolite and the growth of garnet is



and this equation defines the upper boundary of the staurolite stability field. The lack of both staurolite and chlorite could be from a combination of the two reactions. As the metamorphic conditions proceeded, the first reaction consumed all the chlorite, and the mineral assemblage became more Mg-rich. Staurolite broke down and garnet grew as the temperature increased. Staurolite was exhausted, and the reaction ceased, leaving the assemblage garnet + kyanite + biotite. Metamorphic conditions continued to increase until the first sillimanite isograd, defined by the polymetamorphic transformation



This reaction produced fibrolitic sillimanite and can only explain the presence of fibrolite in the garnet Spear (1995). It is unknown whether the presence of the sillimanite needles in the core and at the rim of the garnet were the result of one or two metamorphic events. If the appearance occurred during the same event, then the sillimanite needles formed late in the history of the garnet. Abundant coarse-grained prismatic sillimanite was probably produced from the breakdown of muscovite in the reaction



This also explains the presence of K-feldspar as inclusions in the garnet.

The metamorphic conditions indicated by compositions of the rim of the garnet are retrograde, and the garnet rims are anhedral and resorbed. The mineral assemblage should change through the retrograde metamorphism. The absence of chlorite and staurolite and the presence of muscovite and euhedral sillimanite in the matrix indicates that any chlorite and staurolite that were present did not react to produce garnet.

The AFM diagram indicates that the composition of the inclusion biotite is distinct from the matrix biotite. The mineral assemblage present in the matrix is different from the mineral assemblage that was present at the beginning of the garnet's growth. The presence of high-pressure phases such as rutile near ilmenite is an indication that metamorphic conditions changed through time. Was the change due to one continuous metamorphic event or to a series of metamorphic events that disrupted the mineralogical sequence of the earlier episode? Investigation into the zoning patterns within the garnet could give answers to this question.

III

Garnet Zoning

Mineral zoning results from continuous reactions and intergranular (matrix) and intragranular (volume) diffusion during the mineral's growth (Spear and Selverstone, 1983; Florence and Spear, 1995; Anderson and Olimpio, 1977). Hollister (1966), Thompson (1976), Tracy (1976), Trzcinski (1977), Spear (1983), and Loomis (1982) presented models of garnet zoning that were due to continuous reactions. Tracy and Dietsch (1982), Florence and Spear (1991), Anderson and Buckley (1973), Loomis (1978), and Bethune and Laduron (1975) presented models for garnet zoning due to diffusion.

The processes of garnet growth by continuous reactions and ionic diffusion each create characteristic zoning profiles for the major and some minor elements. In garnet, the profile of the solid solution end-members almandine, spessartine, grossular, and pyrope can be used to distinguish between zoning due to growth processes and garnet zoning resulting from ionic diffusion.

Quantitative microprobe analyses were taken on a traverse across the entire garnet. This is represented in Figures 3.1, 3.2, and 3.3 by the line across the qualitative picture. Below each micrograph is the quantitative zoning profile, and the left side of the profile corresponds with the left side of the picture for Sample 3, and the top of the micrograph for Samples 1 and 2. The graph is the mole fraction of the garnet end-members, spessartine, grossular, pyrope, almandine, and the $\text{Fe}/(\text{Fe} + \text{Mg})$ value versus the distance along the garnet. The quantitative zoning profiles that accompany each micrograph have many similar features and some noteworthy differences.

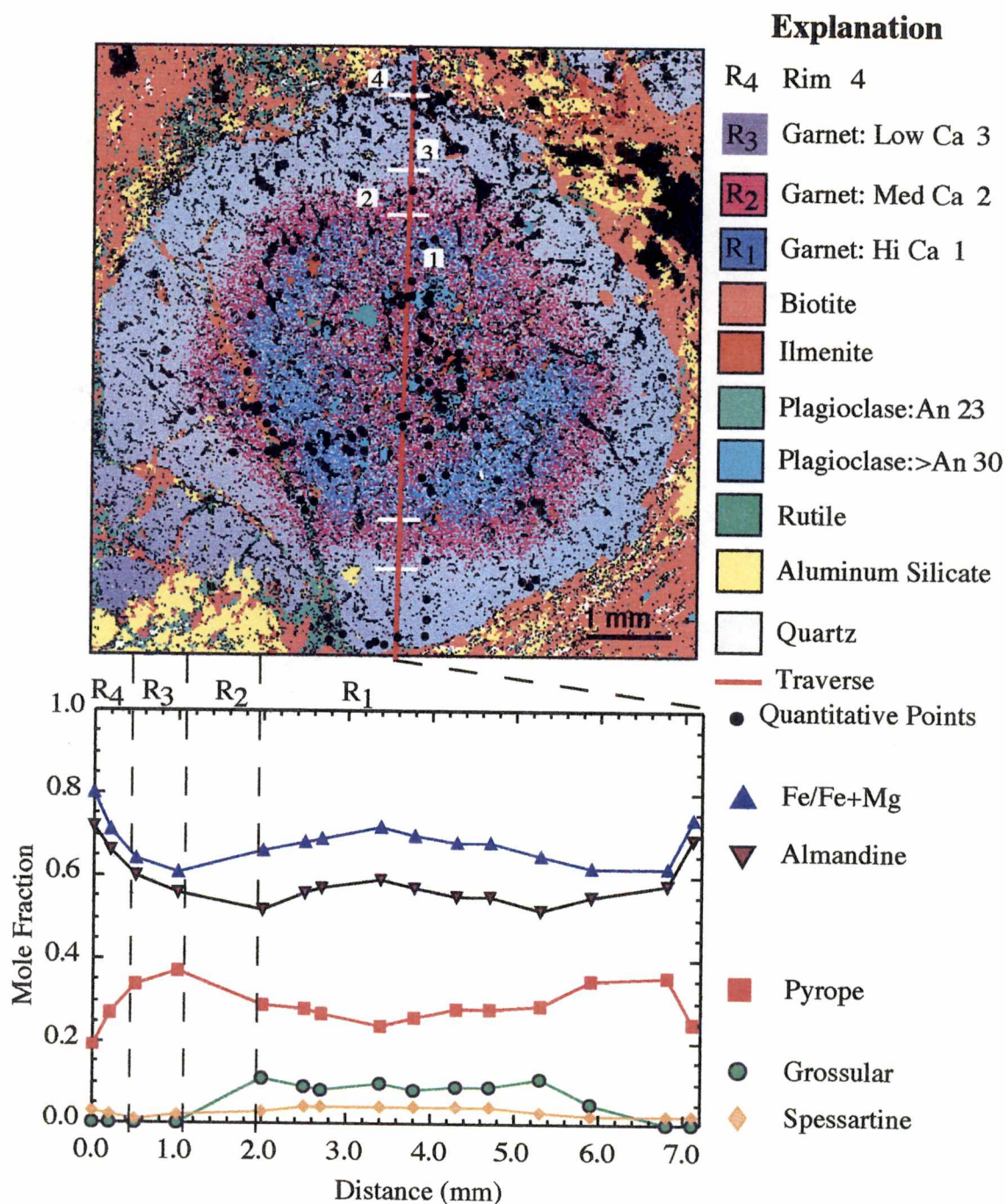


Figure 3.1 Garnet compositional profile and the corresponding micrograph of Sample 1. Pl = plagioclase; An = anorthite; R = region. The black dashed lines represent the boundaries of the regions used in the study, while the red dashed lines represent possible extra regions within the garnet.

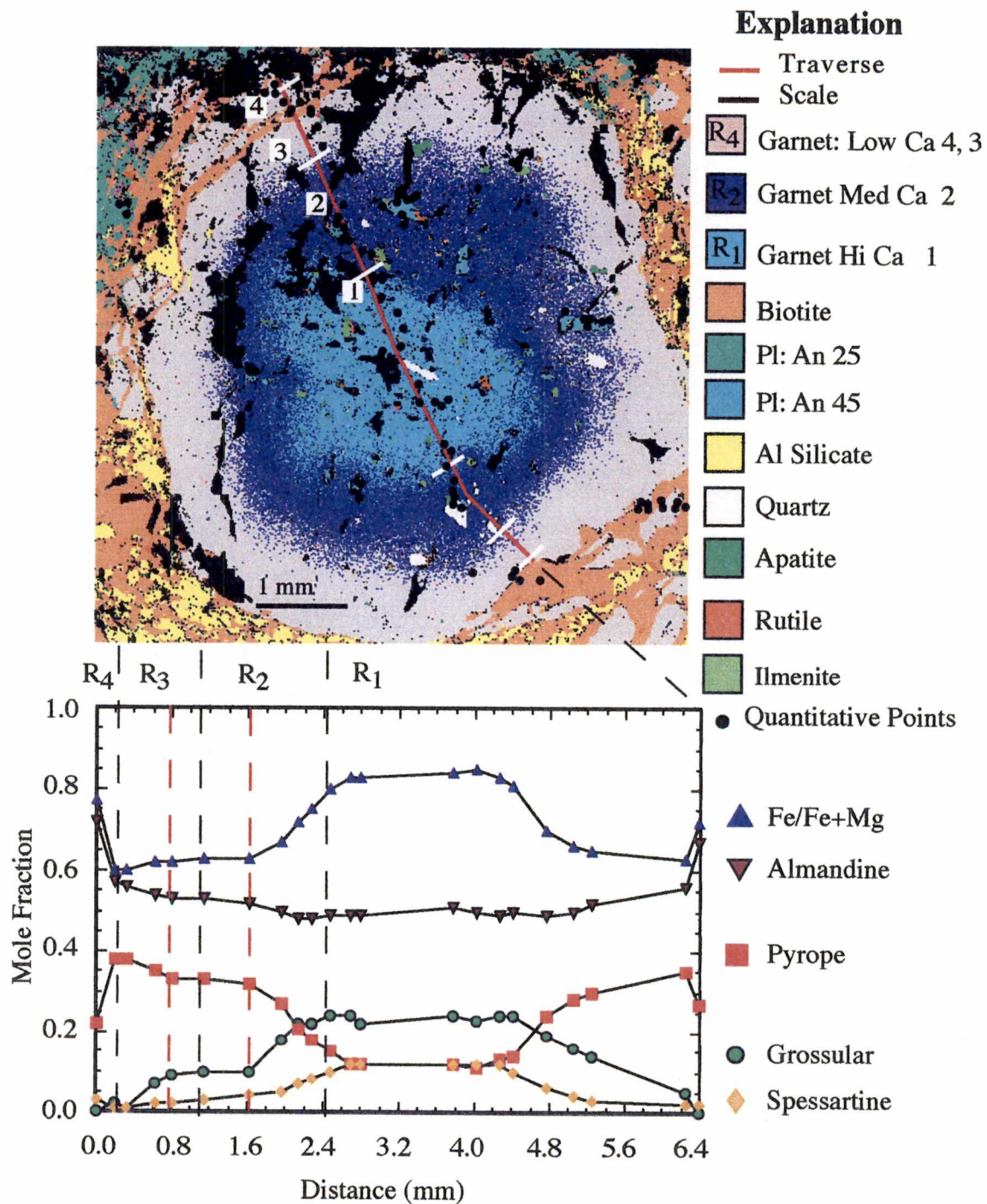


Figure 3.2 Garnet compositional profile and the corresponding micrograph of Sample 2. Pl = plagioclase; An = anorthite; R = region. The black dashed lines represent the boundaries of the regions used in the study, while the red dashed lines represent possible extra regions within the garnet.

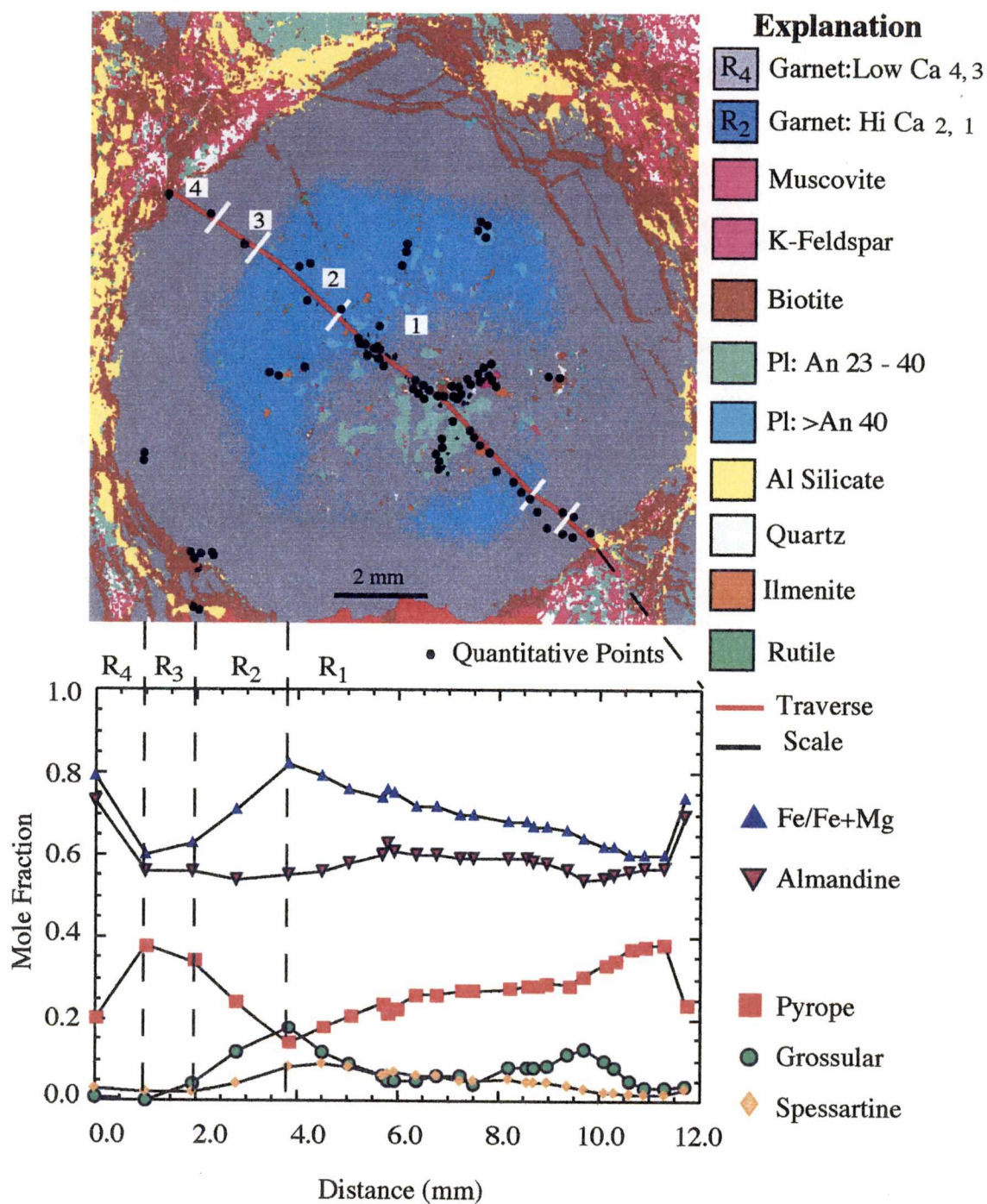


Figure 3.3 Garnet compositional profile and the corresponding micrograph of Sample 3. Pl = Plagioclase; An = Anorthite; R = Region.

The profiles for $\text{Fe}/(\text{Fe} + \text{Mg})$, almandine, and spessartine decrease with a steep slope from the rim. Pyrope has a steep increasing slope from the rim, while grossular has an increasing slope for Sample 2, but the other two samples flatten out at the rim.

Starting at the matrix-rim interface, most of the profiles are characteristic of retrograde diffusion processes (Tuccillo, 1990; Tracy, 1982; Yardley, 1977). The one exception is the first 0.2 mm of the traverse for grossular in Sample 2. The trends of the profiles start to become different after the first 0.5 -1.0 mm. The profiles for all samples have an increase in spessartine and grossular components from rim to core, while the pyrope mole fraction decreases in value from the rim to the core. The profiles of the garnet endmembers for this part of the garnet are characteristic of those made by growth zoning (Tuccillo, 1990; Tracy, 1982; Yardley, 1977; Robinson, 1976).

Trying to make a generalized trend that fits all of the almandine profiles was not realistic. After the retrograde portion of the rim, the almandine values of the samples decrease for the first 2.0 – 3.0 mm, then the values of Samples 1 and 3 increase to the center, while the values of Sample 2 have a flattened almandine profile.

The center of the garnet has different profiles for all of the samples. Sample 2 has flattened profiles across the center that are characteristic of homogenization due to volume diffusion. Sample 3 has patterns that indicate growth zoning across the center, while Sample 1 has a “caldera” pattern for the grossular, a flattened pattern for the spessartine, and a pyrope profile that appears to be typical of growth zoning. It is important to note that the shapes of the profiles for Samples 1 and 2 are symmetric

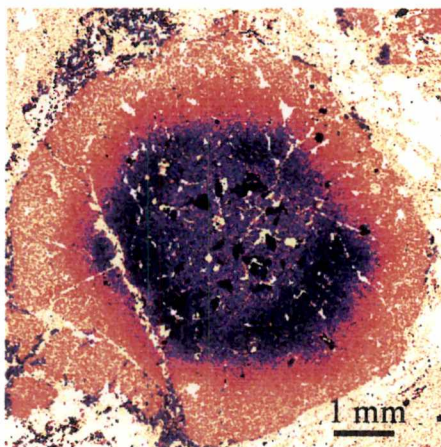
around the center, but the shape of the traverse for Sample 3 is asymmetric. This asymmetry for Sample 3 is evidence of fracturing within the core of the garnet. The inconsistencies in the complex zoning profiles of the samples eventually forced a closer inspection of all the profiles. I had to abandon the idea that the lines of the profiles represent a continuous history from core to rim, and an alternate method of evaluating the compositions of the garnets was used. These observations will become evident further on in this chapter.

Micrographs

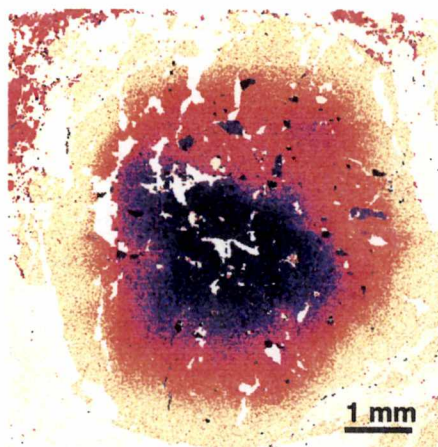
The micrographs above the zoning profiles in Figures 3.1, 3.2, and 3.3 were assembled from qualitative x-ray images collected using the electron microprobe and help to show what created the complex zoning profiles of the samples.

Using the data collected for each element, qualitative x-ray images were created in the computer program *Transform PPC 3.4*. Examples of the images for the elements are presented in Figure 3.4a-c, and all the other images of the elements are in Appendices 1a, 2a, and 3a. The three images are based on the number of calcium k_{α} counts, and similar images were created for Si, Al, Ti, Mg, Fe^{2+} , Mn, K, Na, S, and P. The calcium images presented in Figures 3.4a-c indicate that the cores of the garnets had a higher concentration of calcium and consequently a higher grossular mole fraction than the rim. Other interesting features are the different regions that seem to have been altered to later conditions, the euhedral inner region that is rotated relative to the outer region (Figure 3.4c), and the calcium-rich inclusion trails in Figure 3.4c.

a.) Sample 1

Ca K α counts

b.) Sample 2

Ca K α counts

c.) Sample 3

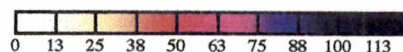
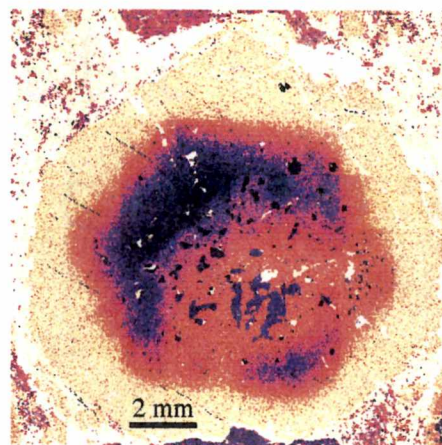
Ca K α counts

Figure 3.4 Qualitative images of Samples 1, 2, and 3 produced from the x-ray scans. The scale bar represents the counts collected from the electron microprobe that were given a color code in the program *Transform PPC*.

Figures 3.5a-c are the Fe/(Fe + Mg) images for the three samples created with the Mg and Fe data. The images indicate that the core of the garnet had a higher Fe/(Fe + Mg) ratio, and the area at the rim and close to fractures has a greater concentration of Fe, probably because of diffusion of Fe between garnet and the matrix and the fracture biotite. Another interesting feature of the images is that many of the pieces of garnet in the matrix have alteration from rim to core.

Masks were created for each mineral to block out data that was not needed to make a certain mineral. To make the image of the garnet it was necessary to distinguish between the Ca^{2+} in plagioclase and the Mg and the Fe^{2+} found in biotite. This was done using the masking code in the program *Transform PPC 3.4*:

$$\text{Garnet_Fe_Mask} = \text{GE}(\text{S3_Fe_Data}, 90) * \text{GT}(\text{S3_Al_Data}, 180).$$

The symbols GE, GT, LT, and LE are logical macro operators in the program *Transform* that allow only a certain range of numbers to exist. GE allows only counts equal to and above 90 to remain in the new matrix. All the other points are set to zero. The Garnet_Fe_Mask allows only the garnet to appear in the resulting image. Figures 3.6(a-f) are examples of masks created for the minerals, garnet, biotite, muscovite, Al silicate, and plagioclase in Sample 3. All other mineral masks appear in Appendices 1b, 2b, and 3b. While masking out the plagioclase, it was noted that there were regions within the garnet itself that contained different levels of Ca^{2+} . Using the transform code

$$\begin{aligned} \text{Garnet_High_Ca_Mask} = & \text{GE}(\text{S3_Al_Data}, 220) * \text{GE}(\text{S3_Ca_Data}, 60) \\ & * \text{LT}(\text{Na_Data}, 20) \end{aligned}$$

different regions of garnet were created.

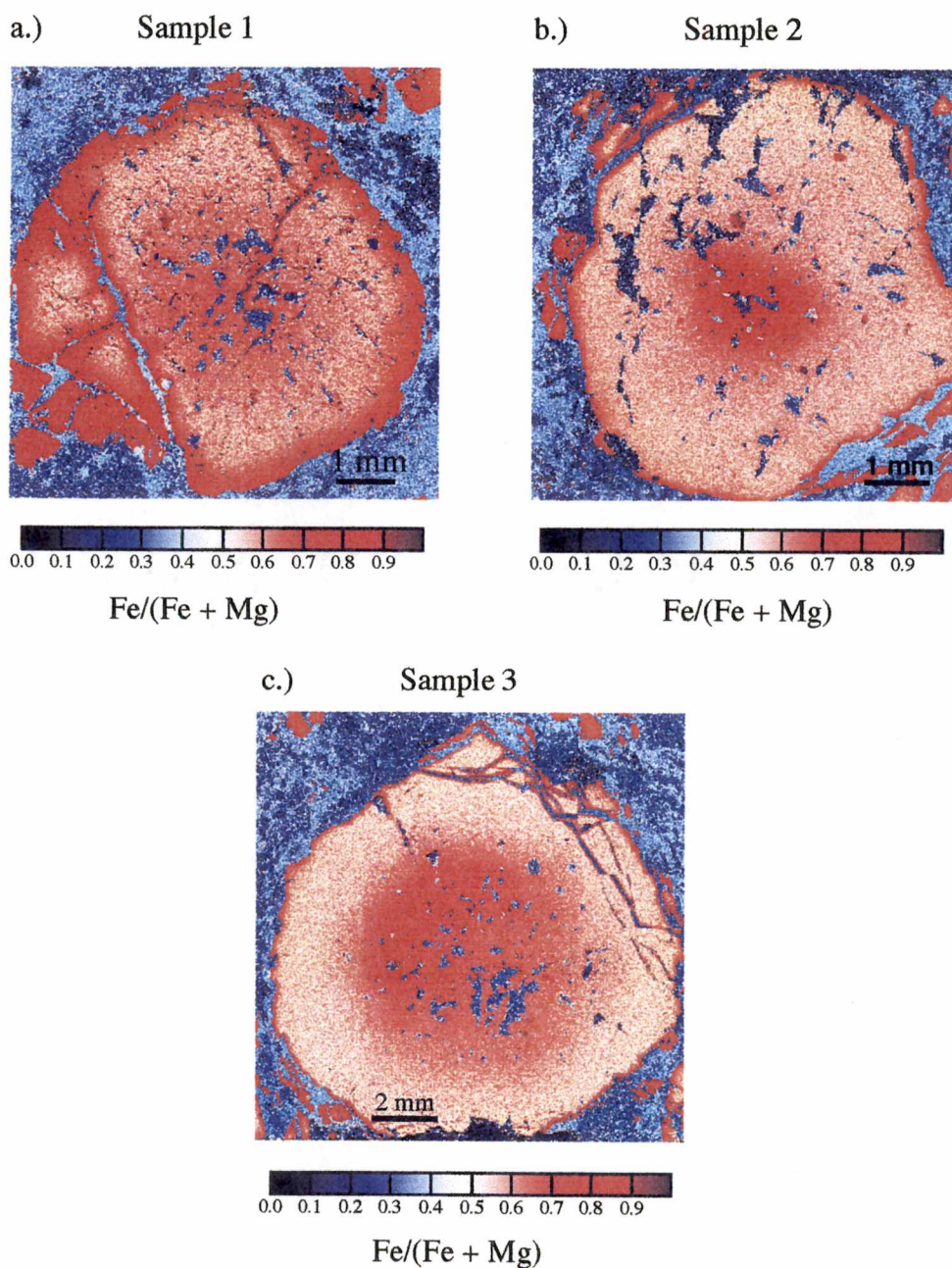


Figure 3.5 Qualitative images of the $\text{Fe}/(\text{Fe} + \text{Mg})$ ratio for Samples 1, 2, and 3. The images were produced from the x-ray scans for the elements Fe and Mg. The numbers on the scale bar represent the counts $\text{Fe}/(\text{counts Fe} + \text{counts Mg})$ collected from the electron microprobe. The numbers were given a color code in the program *Transform PPC*.

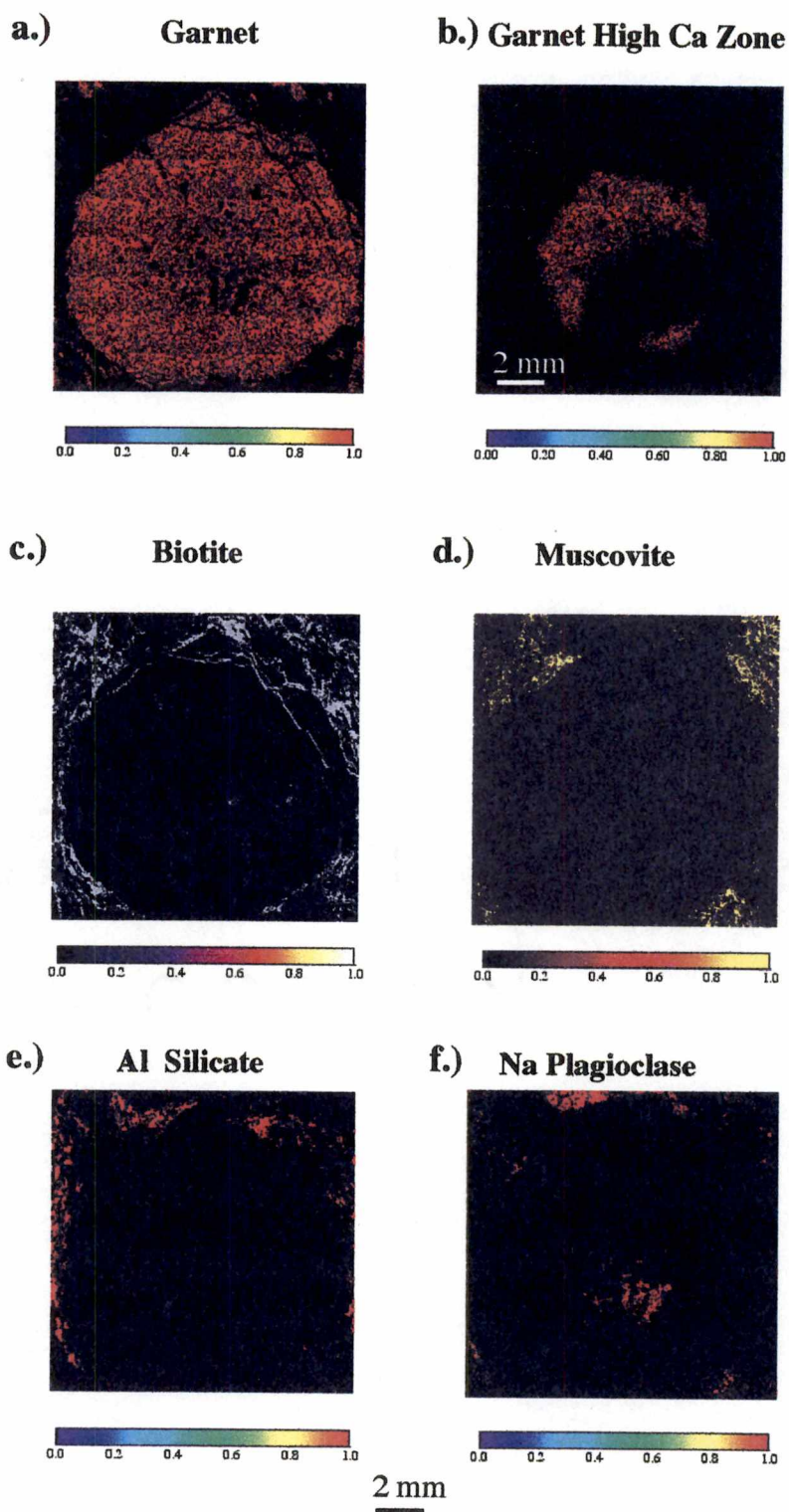


Figure 3.6 Some of the images that were created from the mineral masks used to reproduce the thin section of Sample 3. These masks were made from the elemental transform images.

Figures 3.6a and 3.6b are two images of Sample 3. Figure 3.6b is an important figure in the understanding of the garnet profiles and the history of the garnet. Figure 3.6b defines the hexagonal shape of an euhedral garnet that was fractured at a later time.

Figures 3.7a-f represent part of the process used to make the final micrographs that are shown in Figures 3.1, 3.2, and 3.3. The computer code

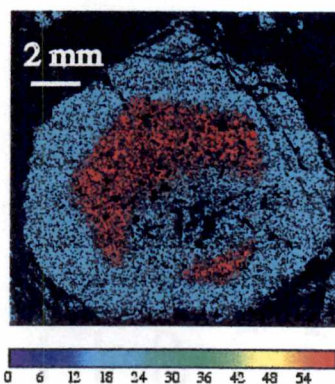
```
M 1 = 20 * Gt_Mask + 40 * Garnet_Ca_Mask
M 1a = LE (M 1, 60)
M 1b = M1 * M1a
```

created the image in Figure 3.7b. This image shows an euhedral inner garnet that fractured, and the material inside the fracture grew under the same conditions as the outer shell. It should also be noted that the inner region is rotated differently than the outer region. The computer code

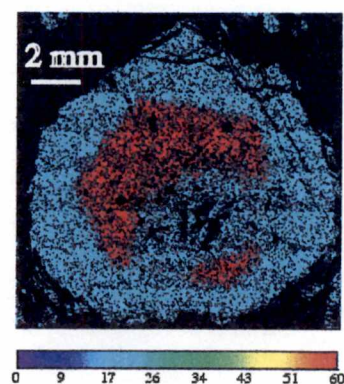
```
M 2 = M 1b + (80 * Bt_Mask)
M 2a = LT (M 2, 100) * GE (M 2, 80)
M 2b = M1b + (M2 * M2a).
```

created the Micrographs 3.7c and 3.7d. This step adds biotite to the micrograph. The numbers 100 and 80 represent a range in values that the mineral biotite can exist, without any overlap, and this gives the programmer control over the numbers. The making of M 2a was important because it cleared the picture of numbers created by overlap. With the help of the computer program *View 3.03* each mineral range was given a specific color. This process continued until all minerals were placed on the micrograph. Samples 1 and 2 went through a similar process and the technique described for Sample 3 was used to make the micrographs for the other samples that are shown in Appendices 1c, 2c, and 3c.

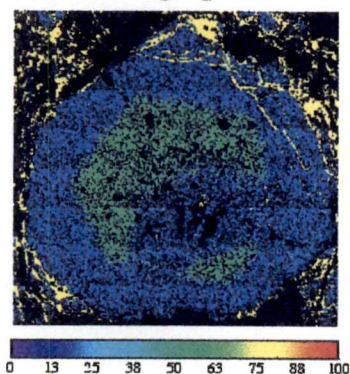
a.) Micrograph 1



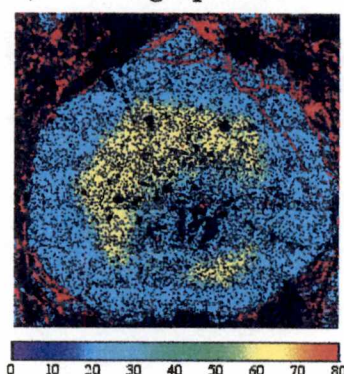
b.) Micrograph 1b



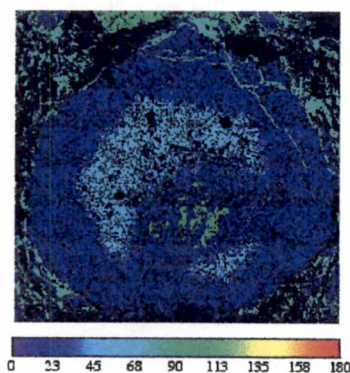
c.) Micrograph 2



d.) Micrograph 2b



e.) Micrograph 3



f.) Micrograph 3b

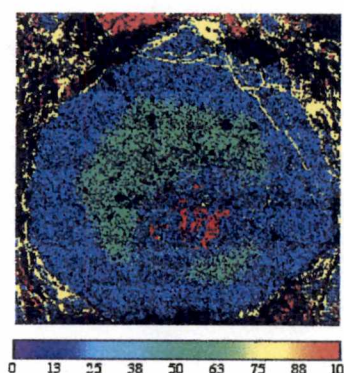


Figure 3.7 Rebuilding of the thin section for Sample 3. The colorbar is based on a scale from 1-254 and each mineral was given a particular range. **a-b)** The top two micrographs are of the high (red) and low calcium zones of the garnet. **c-d)** Micrographs 2 and 2b place biotite on the picture. **e-f)** Micrographs 3 and 3b place Plagioclase with An 23 - 35 on the picture. Further explanation is in the text.

Once all minerals were identified, an optional step was to place all quantitative microprobe points on the micrograph. The computer code for this process is with the other computer code in Appendices 1d, 2d, and 3d.

To locate the quantitative analyses, an image was created in *Transform* with a grid over the garnet (Figure 3.8a). The grid divided the 1024 x 1024 pixels of the image for Sample 1 into smaller quadrants, and each quadrant was made of a square number of pixels. Using this image, a photograph was created and the negative from the photograph was enlarged to make a transparent image, with the gridlines of the garnet on it, that would align with the picture of the garnet that was used during the electron microprobe analyses. At the location of the quantitative microprobe points, holes were punched through both surfaces and the position of the coordinates recorded. To make sure that the analyses were located on the correct mineral, especially at boundaries, the elemental masks were opened, and the point was located on the 1024 x 1024 arrays for Sample 1 and the 512 x 512 arrays for Samples 2 and 3. By using combinations of elements it was possible to locate the approximate boundary of two minerals. One example is the boundary between garnet and biotite. Since garnet contains more Fe counts than biotite and very few potassium k_{α} counts, their boundary could be located using the Fe, the Mg, and the K elemental data sets.

Semiquantitative Images

Semiquantitative data were created using the standard qualitative x-ray data that were collected along with the other qualitative x-ray data of the elements. A comparison

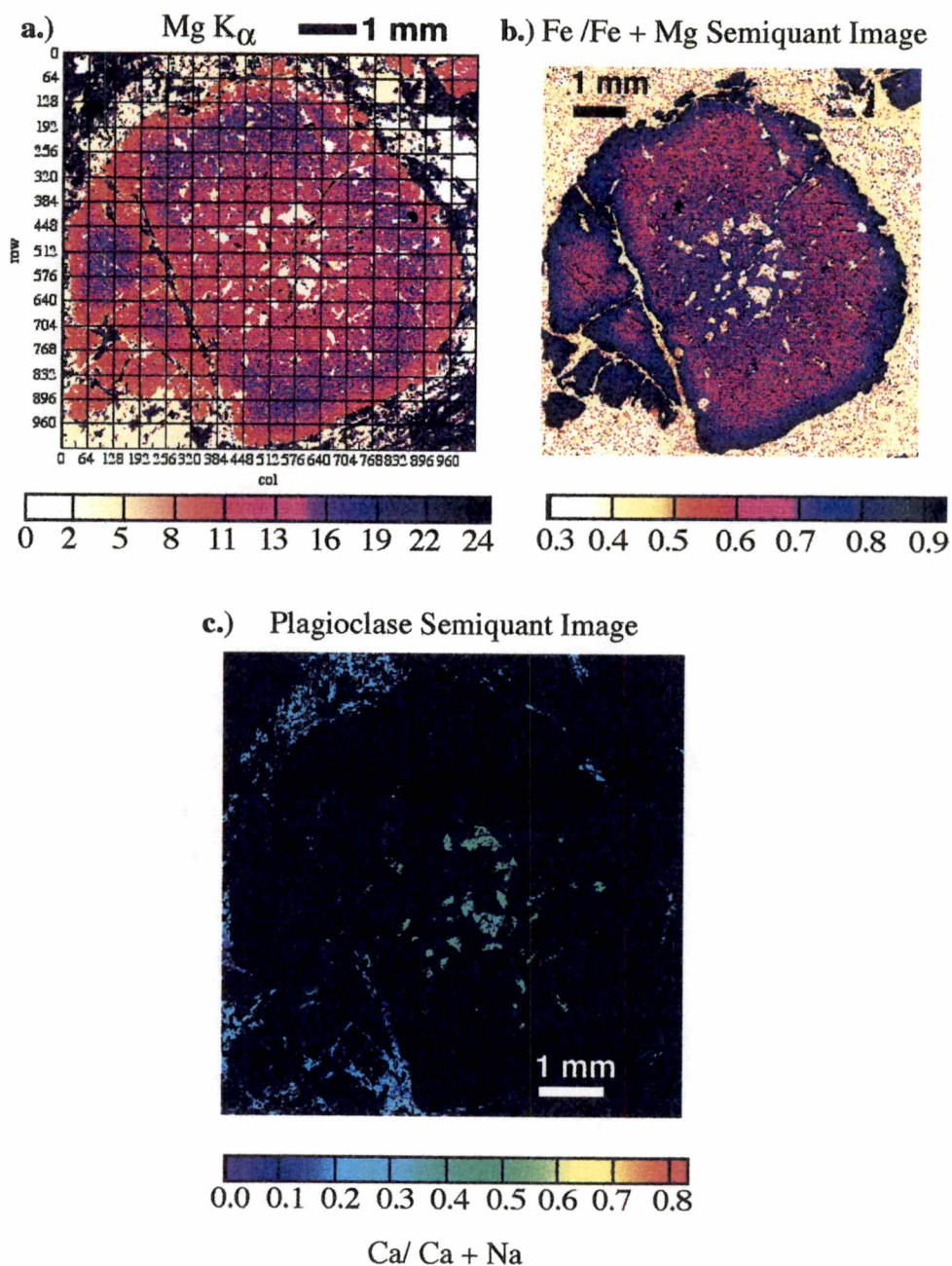


Figure 3.8 Sample 1 semiquantitative analyses. **a)** Shows the Mg K-alpha image for Sample 1 and the grid that was used to locate the quantitative analyses. Each square grid is composed of 64 by 64 pixels. **b)** Fe/(Fe + Mg) semiquantitative map of Sample 1. **c)** Semiquantitative map of the anorthite content in plagioclase for Sample 1.

of the data counts was made between the standard and the sample with the formula

$$\begin{aligned} & (\text{unknown element data count} / \text{Average Standard count of the same element}) \\ & * (\text{Weight \% Element in Standard} / \text{Molecular wt. Element}). \end{aligned}$$

This formula applied to the Ca data set is

$$\text{Ca} = (\text{Plag_Ca_Data} / \text{Average Std counts Ca}) * (\text{Wt.\% Ca_Std.}) / (\text{M.W. Ca})$$

Where Std = standard and M.W. = molecular weight. This process was also applied to the Na Data set. The new data set for Ca was divided by the sum of the Ca and Na Data sets to make a semiquantitative Ca/(Ca + Na) data set. The semiquantitative Ca/(Ca + Na) data set multiplied by the plagioclase mask created the plagioclase anorthite data set. Figures 3.8b and 3.8c are the anorthite and the Fe/(Fe + Mg) semiquantitative images of Sample 1 created from the Ca, Na, Mg, and Fe qualitative *Transform* data sets and the plagioclase and the garnet masks.

Zoning Profiles

Figures 3.1, 3.2, and 3.3 are the result of the piecing together of the qualitative images. The garnets were divided into regions depending on the number of counts of Ca^{2+} in the garnet. This is represented by the different colors inside the garnet in the micrographs. These different regions of calcium concentration are labeled: R_1 = core, R_2 = outer core, R_3 = mantle, and R_4 = the rim. It is difficult to define where the rim ends and the region of the mantle begins, but the transition is defined the best by the point on the quantitative zoning profile where a change in the slope of the curve starts. This change in the slope can be a change in sign or a significant change in the angle of the

line. Most of the boundaries corresponded with the major change in the slope of the zoning profiles.

The region of the garnets bounded by R_4 corresponds with the matrix and garnet rim interface and the first 0 – 1000 μm of the garnet. In this region the trend for the $\text{Fe}/(\text{Fe} + \text{Mg})$ traverse, for all samples, is to decrease until the $R_4 - R_3$ boundary. This boundary for Sample 1 is problematic because the $R_4 - R_3$ could be at 500 μm or at 1000 μm . The $\text{Fe}/(\text{Fe} + \text{Mg})$ values increase across $R_3 - R_2$ to the center of the garnet.

It is in the center that a maximum value for two of the garnets is obtained. Sample 1 has a second maximum that is lower than the rim value, and this is different than the other two samples whose rim maximum is lower than the maximum at the center. Sample 3 has the maximum at the $R_2 - R_1$ interface and then the values decrease to the opposite rim. This is contrary to the symmetrical profile that is expected across a circular garnet.

In all of the samples, the almandine profile has its maximum value at the rim and then the line decreases from the rim through R_4 with a steep slope similar to the $\text{Fe}/(\text{Fe} + \text{Mg})$ trend line. The values for Sample 3 level out across R_3 , then they continue to decrease across R_2 , and then reach the minimum value in the middle of R_2 . The almandine values for Sample 2 decrease across R_3 until the line levels out at the $R_3 - R_2$ interface. The values decrease through R_2 and then level out at the $R_2 - R_1$ boundary. The values for Sample 1 increase to the center, while Sample 3 values increase and level out across R_1 . Sample 2 has a flattened profile across R_1 . The symmetry for the almandine profile is also broken in Sample 3.

Pyrope decreases at the rim, for all of the Samples, with a slope that is a mirror image of the slope for Fe/(Fe+Mg). The mole fraction pyrope continues to decrease through R_3 and R_2 and the values reach the minimum at the $R_2 - R_1$ boundary for Sample 3 and a minimum value in R_1 for Samples 1 and 2. The profiles of Samples 1 and 2 are symmetrical around the center, but Sample 3 increases to the opposite rim. It is also evident that there is a flattening of the profile in Sample 2 near the $R_3 - R_2$ interface.

The grossular content increases in all three samples until the $R_2 - R_1$ boundary. Sample 1 decreases and forms a caldera, and the profile is symmetrical about the center. Sample 2 decreases slightly in R_1 , then flattens out, and it is also symmetrical. Sample 3 has a large decrease in value across R_1 , levels out and then it increases to a second maximum at the island of garnet that is located at 9.0 mm on the traverse. There is also a flattened profile for Sample 2 that extends from 0.2 mm from the $R_3 - R_2$ interface, to 0.4 mm into R_2 .

Spessartine displays a profile that increases for all of the samples towards R_1 . Samples 1 and 2 have flattened profiles through R_1 and they are symmetrical, while the profile for Sample 3 decreases to the other rim and it is asymmetrical.

One noticeable difference between the three profiles is that Sample 2 has flattened profiles in the center that are indicative of diffusion at elevated temperatures, while Sample 1 has a flattened profile for grossular and spessartine in the center. Are these remnant profiles of an early homogenization of the garnet or are they caused by diffusion at a later time? Sample 3 profiles indicate that there is a distinction in how the two halves of the garnet grew.

One can also speculate if the samples were cut through the middle of the garnet, or sliced through part of the garnet's outer regions. This would produce a zoning profile with an incomplete history. Three ways to approach this problem are: to cut through the remaining piece of the garnet and calculate the approximate radius from the remaining garnet wedge, or sand down the remaining garnet to see if the diameter of the garnet increases or decreases. If the diameter increases, then the cut was not made through the center. An easier way to estimate the placement of the cut is to inspect both halves of the garnet. The thickness of the blade would cut out the exact center of the garnet and leave two halves that are approximately equal. The garnets in this study had two equal halves left over after they were cut.

A combination of both growth zoning and diffusion processes created the chemical zoning profiles of the three samples that were presented in this section. The patterns of increases in almandine and spessartine and the decrease of pyrope, at the rim, are characteristic of retrograde diffusion (Yardly, 1977; Tracy, 1976; Robinson, 1991; Tucillo, 1990). The decreasing bell-shape profiles of grossular and spessartine from R_1 to R_3 are characteristic of growth zoning (Robinson, 1991; Tracy, 1976). Sample 2 has the flattened profile at the center that is characteristic of high-grade homogenization that is caused by diffusion. Samples 1 and 3 have complex profiles that indicate that the profiles were altered from those that were originally at the center of the garnet. The change in Sample 1 is less obvious than the change in Sample 3.

If there is no alteration of the profiles from retrograde diffusion, then the $\text{Fe}/(\text{Fe}+\text{Mg})$ gives an indication of the change in temperature through the garnet's history. The higher the $\text{Fe}/(\text{Fe}+\text{Mg})$ values represent higher temperature conditions. The high $\text{Fe}/(\text{Fe}+\text{Mg})$ values at the core of the garnets are indicative of high temperatures. The temperature decreased through R_2 and perhaps the flattened profiles of Sample 2 indicate an isothermal period that crossed from R_2 into R_3 . This is not supported by the $\text{Fe}/(\text{Fe}+\text{Mg})$ profiles for Samples 1 and 3. Of the three garnets that were studied, Sample 2 contains the profiles that best represent an intact history of the garnet. If one assumes that a change in the slope of a zoning profile indicates a change in the metamorphic conditions, then there are five to six metamorphic events represented in Sample 2. The dashed red lines in Figure 3.2 represent the other possible regions of the garnet.

The complex zoning profiles for the garnets of this study indicate that more than one metamorphic event occurred through the history of the garnet's growth. The first period of garnet growth was altered during a high temperature metamorphic event. The evidence for this event is in the flattened profiles in the region R_1 . A second metamorphic event occurred at a lower temperature and pressure and this is recorded in the profiles through the regions R_2 - R_3 . It was during this event that the large fractures in the core of the garnets were made and recrystallized. The last metamorphic event created the diffusion at the rim of the garnet and the large fracturing that cut through all of the regions of the garnet. The intensity of this last metamorphic event had to be low enough and of a short enough time period that it did not reset the interior of the garnet to the last metamorphic conditions.

IV

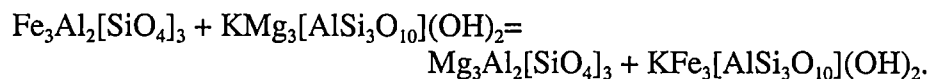
Thermobarometry

Introduction

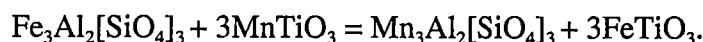
Quantitative thermobarometry is necessary to determine the metamorphic history of a region. It is important not to oversimplify the metamorphic history by taking each calculated P-T analysis as an instantaneous event, but as a brief moment when peak temperature conditions were locked into a mineral (Spear, 1983).

The calculations for thermobarometry were done with the use of the computer program *Thermobarometry 2.1* by Spear and Kohn (1999). Temperatures for the three samples studied were calculated using the garnet-biotite exchange thermometer of Ferry and Spear (1978) and the garnet-ilmenite exchange thermometer of Pownceby (1987).

The garnet-biotite thermometer of Ferry and Spear uses the Berman (1990) activity model for garnet, and is based on the FeMg₋₁ exchange between garnet and biotite in the equation

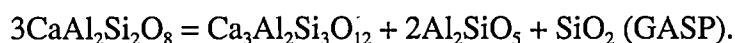


The lack of biotite inclusions within Sample 2 made it necessary to use the garnet-ilmenite thermometer of Pownceby (1987) with the garnet activity models of Ganguly and Saxena (1984). This thermometer is based on the exchange of Fe²⁺ and Mn²⁺ between garnet and ilmenite in the equation

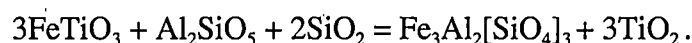


Pownceby (1987) compared the garnet - biotite and the garnet - ilmenite thermometers and found that for temperatures between 500 and 750 °C the garnet - ilmenite thermometer calculations were 30 - 150 °C greater than the garnet - biotite exchange thermometer of Ferry and Spear (1978). I found that relationship was true for most of my calculations.

Pressures were calculated with the garnet - anorthite - aluminum-silicate-quartz (GASP) barometer of Koziol and Newton (1989). This barometer is based on the breakdown of anorthite to grossular in the net transfer reaction



Another barometer that was used was the garnet, rutile, ilmenite, aluminum silicate, quartz (GRAIL) barometer of Bohlen (1983). The GRAIL barometer is based on the net transfer reaction



This barometer could also be used in conjunction with the GASP barometer. The two barometers have different slopes to their lines and the intersection of the two lines defines a point in P-T space.

To obtain an accurate temperature - pressure calculation, only the microprobe analyses of adjacent minerals were used. The weight percent oxides for garnet had to be within 1.6 % of 100.0% and the cation totals had to be within 0.01 of 8.00. To make sure that there were no effects from excitation volume, comparisons were made across phase boundaries in 1 - 3 µm increments. The weight percent total for biotite

had to be within 96.0 % of 100.0 %. Plagioclase analyses had to have weight percent totals within 1.6 % of 100.0 %.

There is a correlation between a garnet's size and the degree of homogenization that occurs in the garnet end-member zoning profiles. Garnet grains greater than 5 mm in diameter resist homogenization and have a greater probability of recording the growth history (Spear, 1990). The size, quality, and the number of inclusions within the garnet determined which garnets were studied under the electron microprobe. Mineral inclusions within the garnet were picked for analyses on the basis of their position within the garnet and their lack of chemical zoning.

Accurate thermobarometry calculations require garnet rim and matrix minerals for rim thermobarometry and garnet core and minerals included within the core for core thermobarometry. The complex zoning profiles of these garnets made it necessary to use a scheme that divided the garnet into four regions: R_1 = core; R_2 = outer core; R_3 = mantle; and R_4 = rim. Inclusions from within these zones were analyzed to obtain both accurate P-T conditions and a reliable history of the garnet.

Using the maximum and minimum values from the calculated temperatures and pressures, parallelograms were drawn on a P-T plot for the regions of the garnet where the calculations were made. Table 4.1 contains the maximum and minimum values obtained from the thermobarometers, while Figures 4.1a-c show the calculated thermobarometry for the three samples relative to the aluminum silicate stability field and important univariant curves.

Table 4.1 Temperature and pressure values for the three samples studied relative to the regions of the garnet.

SAMPLE	R ₁	R ₂	R ₃	R ₄
1	490 - 525 ¹ °C	-----	-----	560 - 575 ¹ °C
	5.8 - 6.8 ³ kbars	-----	-----	5.0 - 6.8 ³ kbars
2	550 ⁴ - 560 ⁵ °C	-----	-----	450 ⁴ - 500 ¹ °C
	7.1 - 8.1 ³ kbars	-----	-----	4.9 - 6.0 kbars
3	460 ¹ - 520 ⁴ °C	630 ¹ - 730 ⁴ °C	450 ¹ - 460 ⁴ °C	475 ¹ - 560 ⁴ °C
	5.0 ² - 6.5 ³ kbars	8.5 ³ - 11.0 ³ kbars	3.1 ³ - 5.3 ³ kbars	3.5 ² - 6.0 ³ kbars

R₁ = Core; R₂ = Outer- Core; R₃ = Mantle; R₄ = Rim.

1. Garnet - Biotite; Ferry and Spear with Berman, 1990.
2. GRAIL; Bohlen, 1983.
3. GASP; Koziol and Newton, 1989.
4. Garnet - Ilmenite; Pownceby, 1987, with Ganguly and Saxena, 1984.
5. Garnet - Ilmenite; Pownceby, 1987.

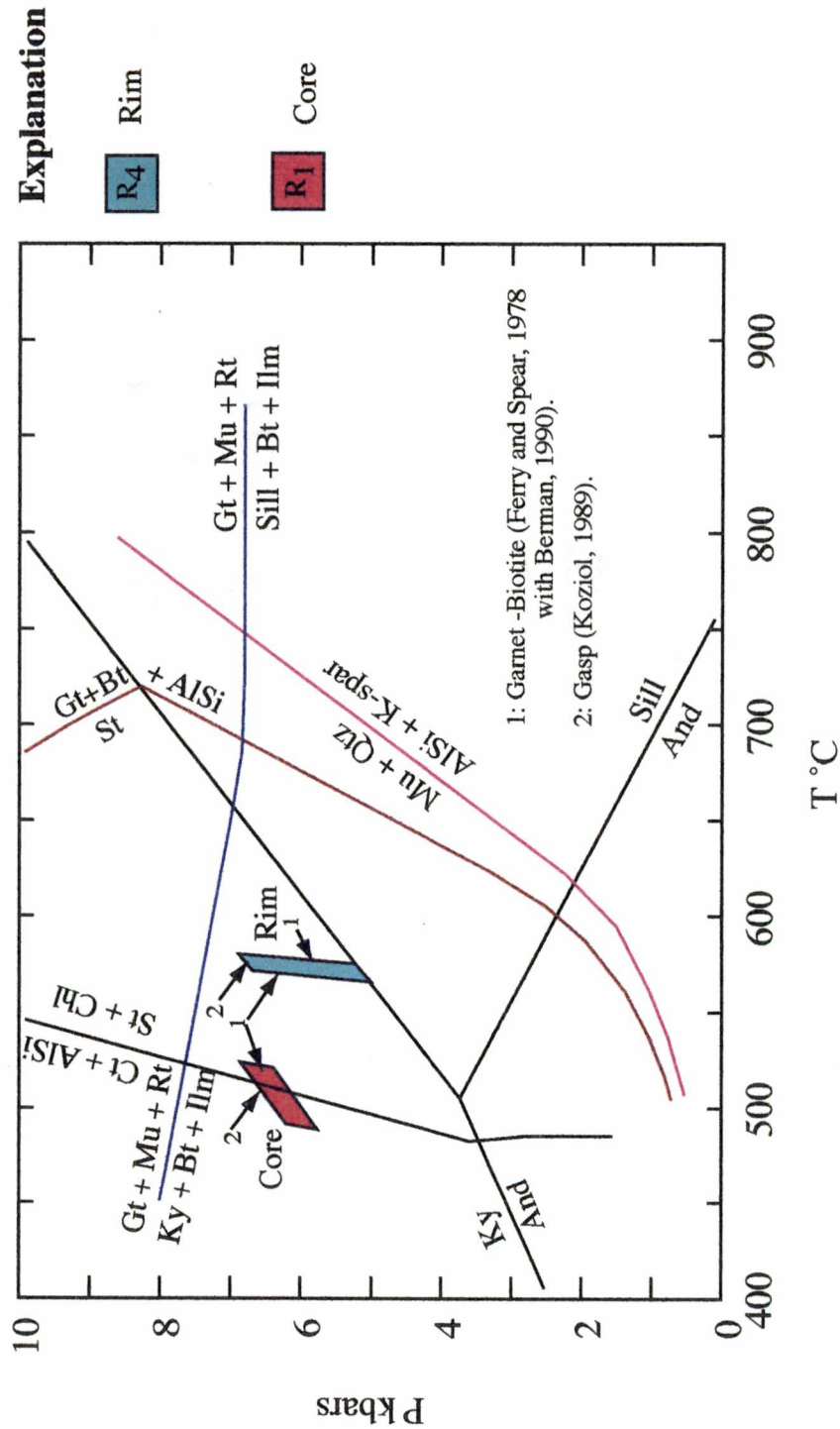


Figure 4.1 Thermobarometry. a) Comparison between the core and the rim thermobarometry results for Sample 1 relative to the aluminum silicate stability fields and the regions R4 and R1 of the garnet.

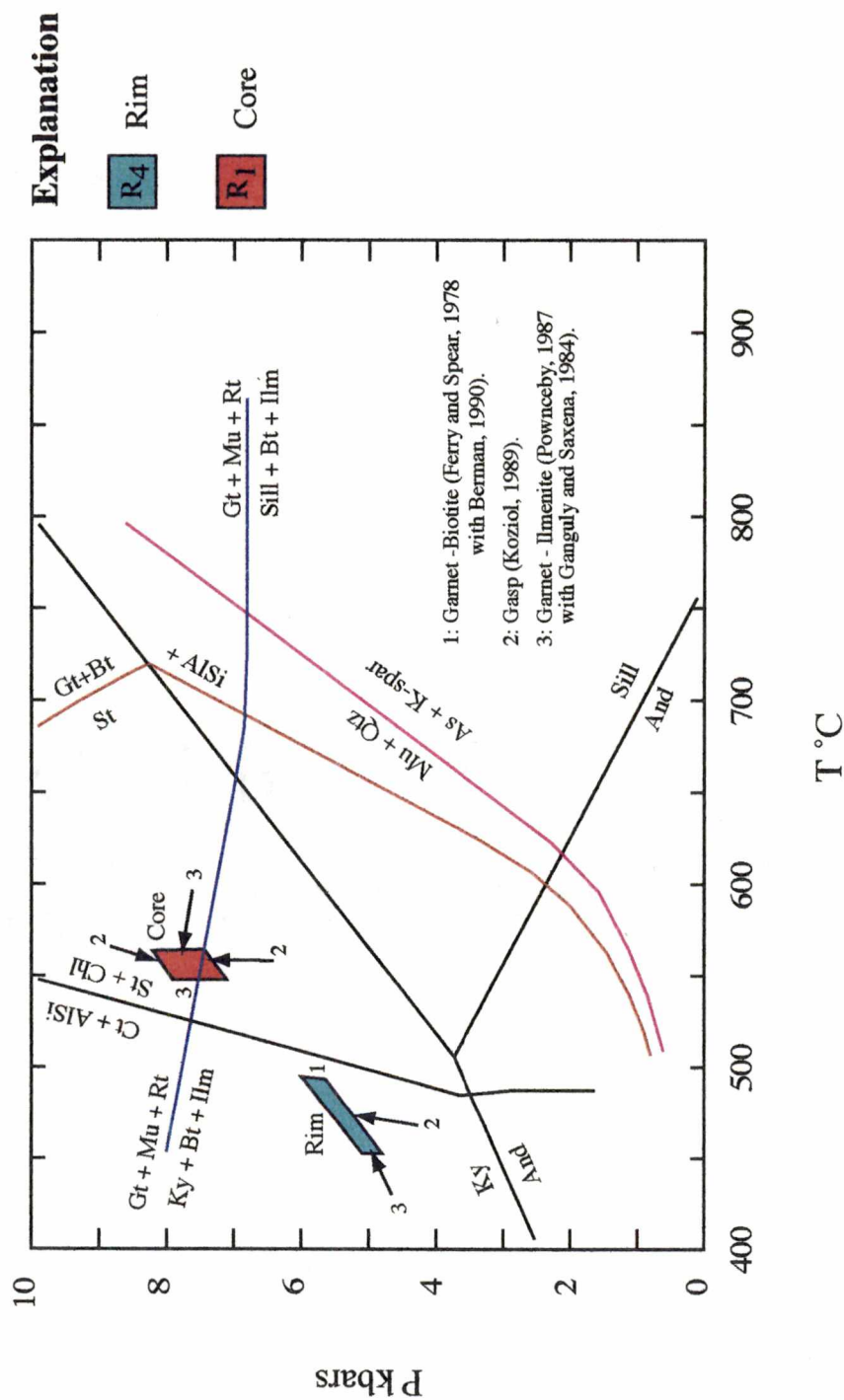


Figure 4.1 (continued) b) Comparison between the core and the rim thermobarometry results for Sample 2 relative to the aluminum silicate stability fields and the different regions of the garnet.

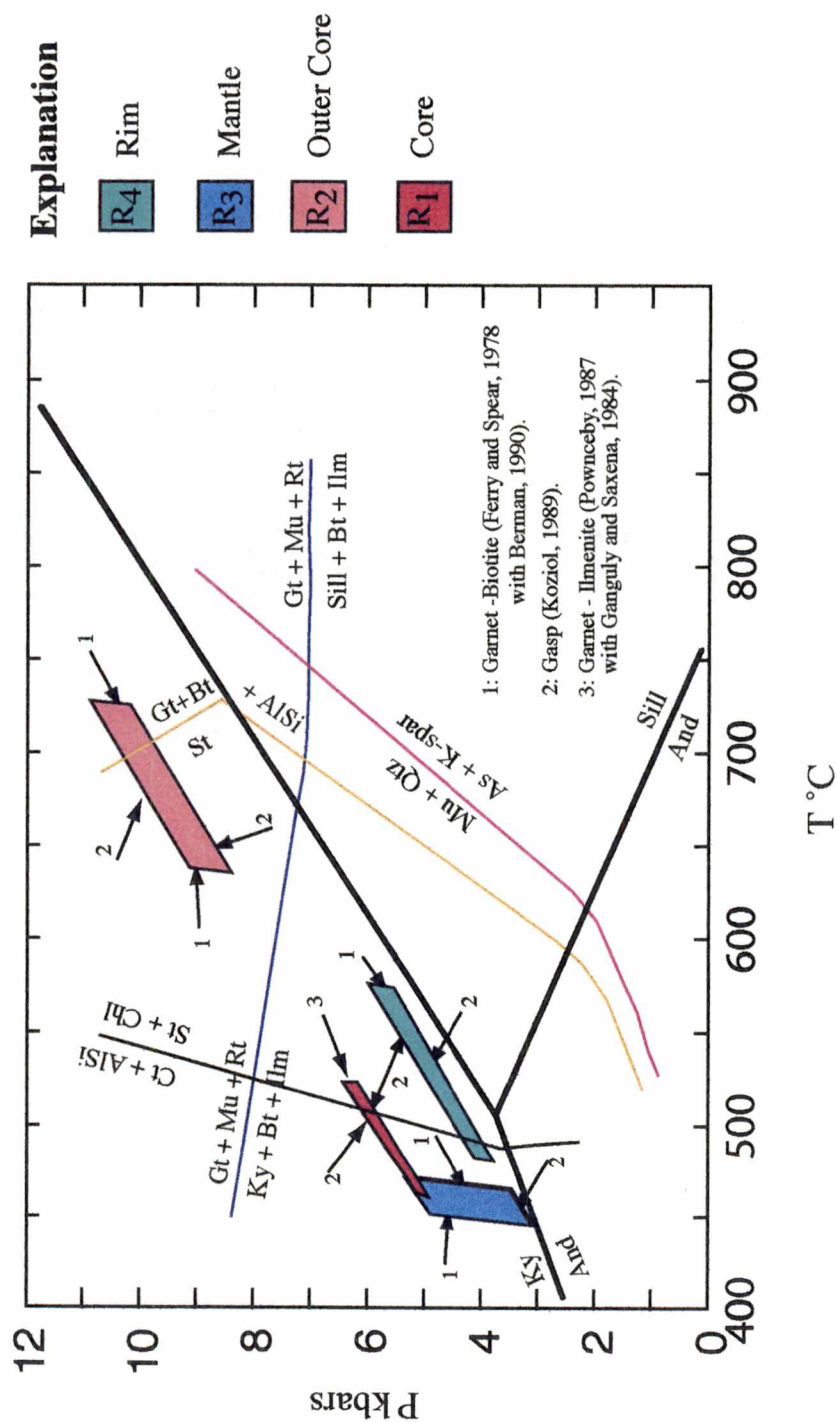


Figure 4.1 (continued) **c)** Comparison between the core and the rim thermobarometry results for Sample 3 relative to the aluminum silicate stability fields and the four regions of the garnet. The numbers by the quadrilaterals indicate the type of thermobarometry that was used to create the maximum and minimum pressures and temperatures.

Samples 1 and 3 are similar because both samples have lower temperatures in the core (R_1) of the garnet, but the pressures are the same. Samples 2 and 3 are similar because both have higher temperatures and pressures in the outercore (R_2) of the garnet than at the rim (R_4). Sample 3 has the core (R_1) temperatures lower than the rim (R_4), while the core (R_1) values for sample 2 are higher than the rim (R_4) values.

Sample 2 contains the least complex zoning profile and its P-T conditions are discussed first. Figure 4.1b shows the garnet history of Sample 2 relative to the kyanite – sillimanite - andalusite boundary curves of Holdaway (1971). Temperature and pressure values for the garnet core (R_1) range from 550 – 560 °C and 7.1 - 8.1 kbars. The rim (R_4) values were only slightly lower at the calculated temperature of 450 - 500 °C, but the pressure was much lower, 4.9 – 6.0 kbars.

The pressure and temperature results shown in Figure 4.1a indicate that Sample 1 had a complicated history because of the recorded core (R_1) temperature values of 490 – 525 °C and pressures ranging from 5.8 - 6.8 kbars. The rim (R_4) values were 560 – 575 °C and 5.0 - 6.8 kbars. Sample 3, Figure 4.1c, has the most complete P-T history because there were abundant mineral inclusions in each zone of the garnet. Temperatures in the core (R_1) were 460 - 520 °C at pressures from 5.0 – 6.5 kbars. Outercore (R_2) values ranged from 630 – 730 °C and 8.5 – 11.0 kbars. The mantle (R_3) values were 450 – 460 °C at pressures of 3.1 – 5.3 kbars. The rim (R_4) temperatures were 475 - 560 °C with pressures of 3.5 – 6.0 kbars.

The low core values of Samples 1 and 3 are contrary to the results of Shireman and Labotka (1985) who obtained values of 730 °C and 7.3 kbars for the core of the garnet in their study. It is not known if the analyses of Shireman were taken in an unaltered region of the garnet, or if the entire garnet was intact, but this example would be similar to Sample 2 of this study. Davidson (1995) also found that some of the core values were very low and concluded that somehow reequilibration occurred in the core of the garnet.

The low pressure and temperature values in the core for Sample 3 needed further investigation and since there was rutile and ilmenite in the core of the garnet, the barometer GRAIL and the garnet-ilmenite thermometer of Pownceby (1987) were used on Samples 2 and 3. GRAIL was also used as a barometer in conjunction with the GASP barometer for both Samples 2 and 3.

Figures 4.2a and 4.2b show the results of the thermobarometry calculations. The intersections of the P –T lines create the triangles in each figure. Sample 2 has a larger temperature and pressure range for Regions 1 and 2 than for Region 4. This indicates that the K_D values were altered. Possible reasons for the differences in temperatures between the garnet-ilmenite and the garnet - biotite thermometers are;

- a) the garnet - biotite temperature is a minimum value.
- b) ilmenites that contain a small mole fraction of manganese have a greater error in the temperature estimation with only a small amount of error from the electron microprobe analysis (Pownceby, 1987).

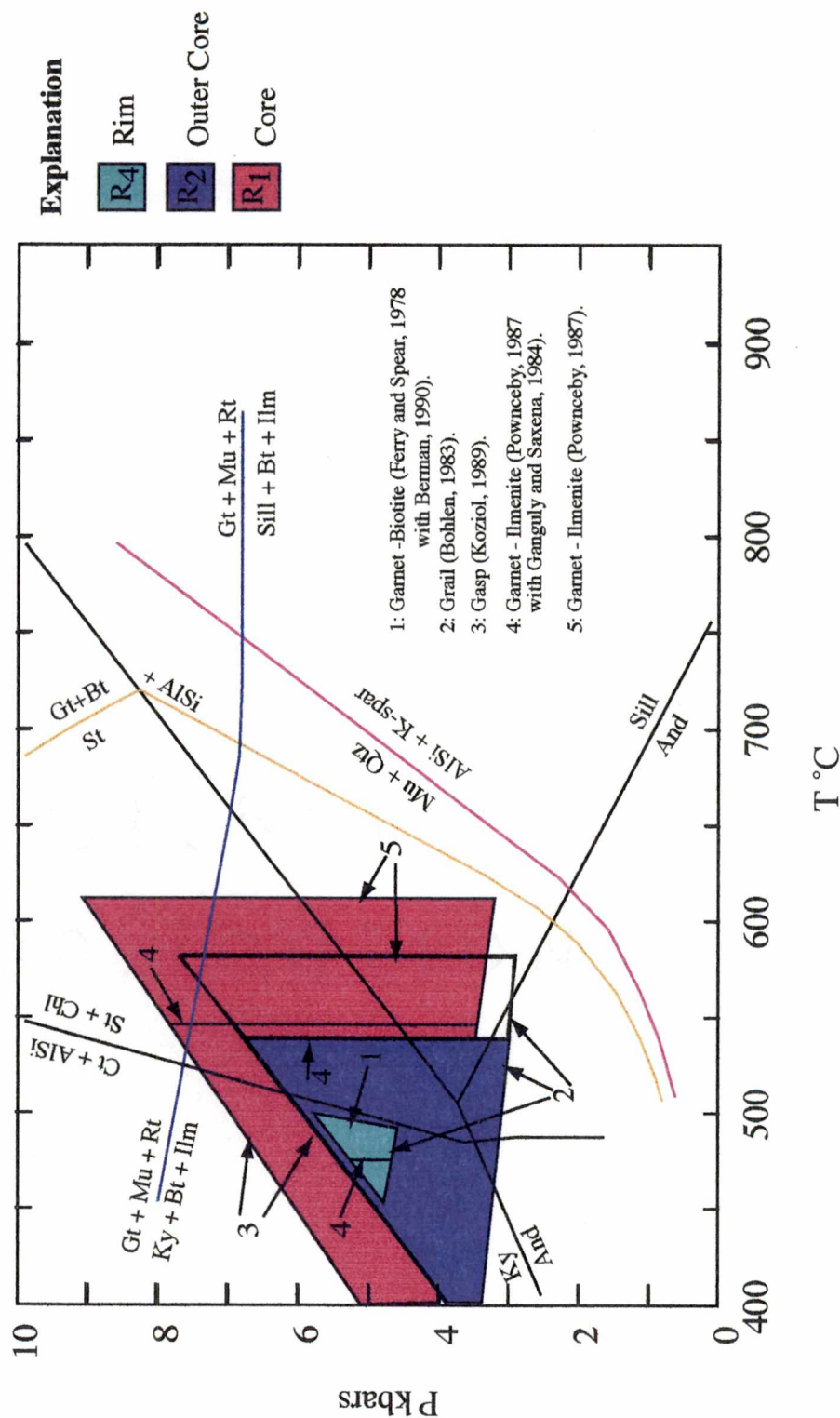


Figure 4.2 Compared Thermobarometry a) Comparison of the intersection points of different thermometers and barometers relative to the regions of R₁ - R₄ for Sample 2. The numbers 1 - 4 on the graph correspond with the type of thermometer or barometer that was used.

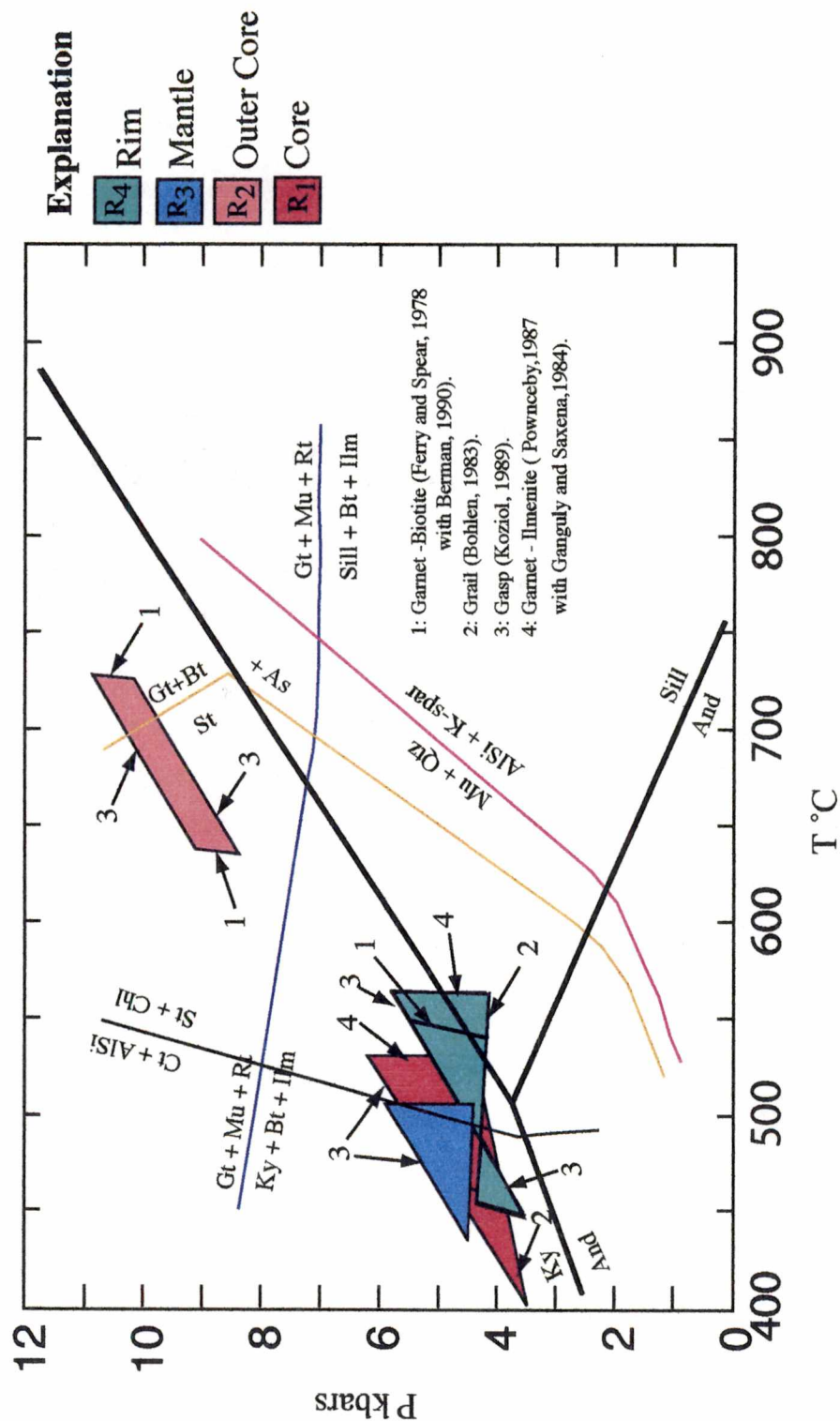


Figure 4.2 (continued) b) Comparison of the intersection points of different thermometers and barometers relative to the regions R1 - R4 for Sample 3. The numbers 1 - 4 on the graph correspond with the type of thermometer or barometer that was used.

c) the increased rate of diffusion for Mn and Fe in Regions 1 and 2.

The rate of diffusion in garnet is slower than the diffusion rate in ilmenite and the closure temperature of the garnet might record a higher temperature if the ilmenite reacts with phases such as biotite and chlorite (Pownceby, 1987).

Table 4.2 compares the results of the thermometers and barometers for the different regions of the garnets. All the thermometers give similar results for Region 4 of the garnet and the range of values is 445 – 565 °C, while the barometers had a range from 3.6 - 5.7 kbars. Both Samples 2 and 3 had the GRAIL $\cap$ GASP (where $\cap$ represents the intersection) values lower than the (garnet – ilmenite) $\cap$ GASP thermobarometry for Regions 1, 3, and 4 of the garnet. The garnet - ilmenite thermometer of Pownceby gives higher values than the same thermometer with the mixing models of Ganguly and Saxena (1984).

The (garnet – ilmenite) $\cap$ GASP thermobarometry had the highest pressures for all regions of each garnet. The results for Region 3 were similar to Region 4, but R_3 had temperatures slightly lower and pressures slightly higher than R_4 for all samples. Region 2, for Sample 3, had only the (garnet – biotite) $\cap$ GASP thermobarometry with an average value of 680 °C, 9.0 kbars, and these results were close to the results for Regions 1 and 2 of Sample 2 for the (garnet – ilmenite) $\cap$ GASP thermobarometry.

Region 1 has perplexing results because the GRAIL $\cap$ GASP, the (garnet – biotite) $\cap$ GASP, and the (garnet – biotite) $\cap$ GRAIL all give much lower readings

Table 4.2 The comparison of the intersection values for different thermometers and barometers for Samples 2 and 3 that were used to create Figures 4.2(a-b). R_1 - R_4 correspond to the regions of the garnet as is described in the text.

Sample	Region	GRAIL ² ∩ GASP ³	(Gt-Bt) ¹ ∩ GASP ³	(Gt-Ilm) ⁵ ∩ GASP ³
2	R_1	< 400 °C @ 3.6 kbars	-----	615 °C @ 9.0 kbars
	R_2	380 °C @ 3.5 kbars	-----	580 °C @ 7.5 kbars
	R_3	-----	-----	-----
	R_4	445 °C @ 4.6 kbars	500 °C @ 5.7 kbars	-----
3	R_1	400 °C @ 3.0 kbars	460 °C @ 4.0 kbars	-----
	R_2	-----	680 °C @ 9.0 kbars ^A	-----
	R_3	440 °C @ 4.4 kbars	445 °C @ 3.9 kbars	-----
	R_4	490 °C @ 3.6 kbars	500 °C @ 3.7 kbars ^A	-----
Sample	Region	(Gt-Bt) ¹ ∩ GRAIL ²	(Gt-Ilm) ⁵ ∩ GRAIL ²	(Gt-Ilm) ⁴ ∩ GASP
2	R_1	-----	615 °C @ 3.3 kbars	550 °C @ 7.5 kbars
	R_2	-----	580 °C @ 2.9 kbars	540 °C @ 6.8 kbars
	R_3	-----	-----	-----
	R_4	490 °C @ 4.6 kbars	475 °C @ 4.5 kbars	475 °C @ 5.3 kbars
3	R_1	450 °C @ 3.3 kbars	530 °C @ 3.6 kbars	530 °C @ 5.6 kbars
	R_2	-----	-----	-----
	R_3	440 °C @ 3.9 kbars	510 °C @ 3.7 kbars	510 °C @ 5.3 kbars
	R_4	500 °C @ 3.6 kbars	565 °C @ 3.5 kbars	565 °C @ 5.1 kbars

1.) Garnet – Biotite: Ferry and Spear with Berman, 1990; 2.) Grail (Bohlen, 1983); 3.) Gasp, Koziol, 1989).

4.) Garnet – Ilmenite (Pownceby, 1987 with Ganguly and Saxena, 1983).

5.) Garnet – Ilmenite, (Pownceby, 1987).

A: Average of the garnet – biotite and GASP intersection values.

than the (garnet – ilmenite) $\cap$ GASP thermobarometer. Another column with the (garnet – ilmenite) $\cap$ GRAIL thermobarometry gives similar values for thermometry with (garnet – ilmenite) $\cap$ GASP, but the pressure values are much lower than the (garnet – ilmenite) $\cap$ GASP. The temperature values for the (garnet – ilmenite) $\cap$ GASP and the (garnet – ilmenite) $\cap$ GRAIL thermobarometry were expected to be close because of the high slope of the garnet – ilmenite line.

Pressure – Temperature Paths

Quantitative thermobarometry calculations give the peak metamorphic conditions of the mineral assemblage being studied. The results of the thermobarometry can then be used to estimate the path that the rock took during its formation (Nesbitt and Essene, 1982; Spear, 1984).

The large arrows in Figures 4.3a-c represent the possible P – T paths for the three samples. The paths in the figures are three logical connections between the temperatures and pressures that were calculated by thermobarometry. The paths aren't calculated from the zoning profiles of the garnet, and they are not based on evidence from mineral inclusions. Path 1, for all samples, is the most direct route that the minerals took from core to rim through P – T space.

Path 1 for Sample 1 in Figure 4.3a is the reverse of Sample 2 and it is indicative of a reverse P – T loop. Path 1 of Sample 2 follows a route consisting of cooling and decompression. Path 1, for Sample 3, could also be counterclockwise, similar to Sample 1. If one uses Region 2 of Sample 3 as the original core conditions,

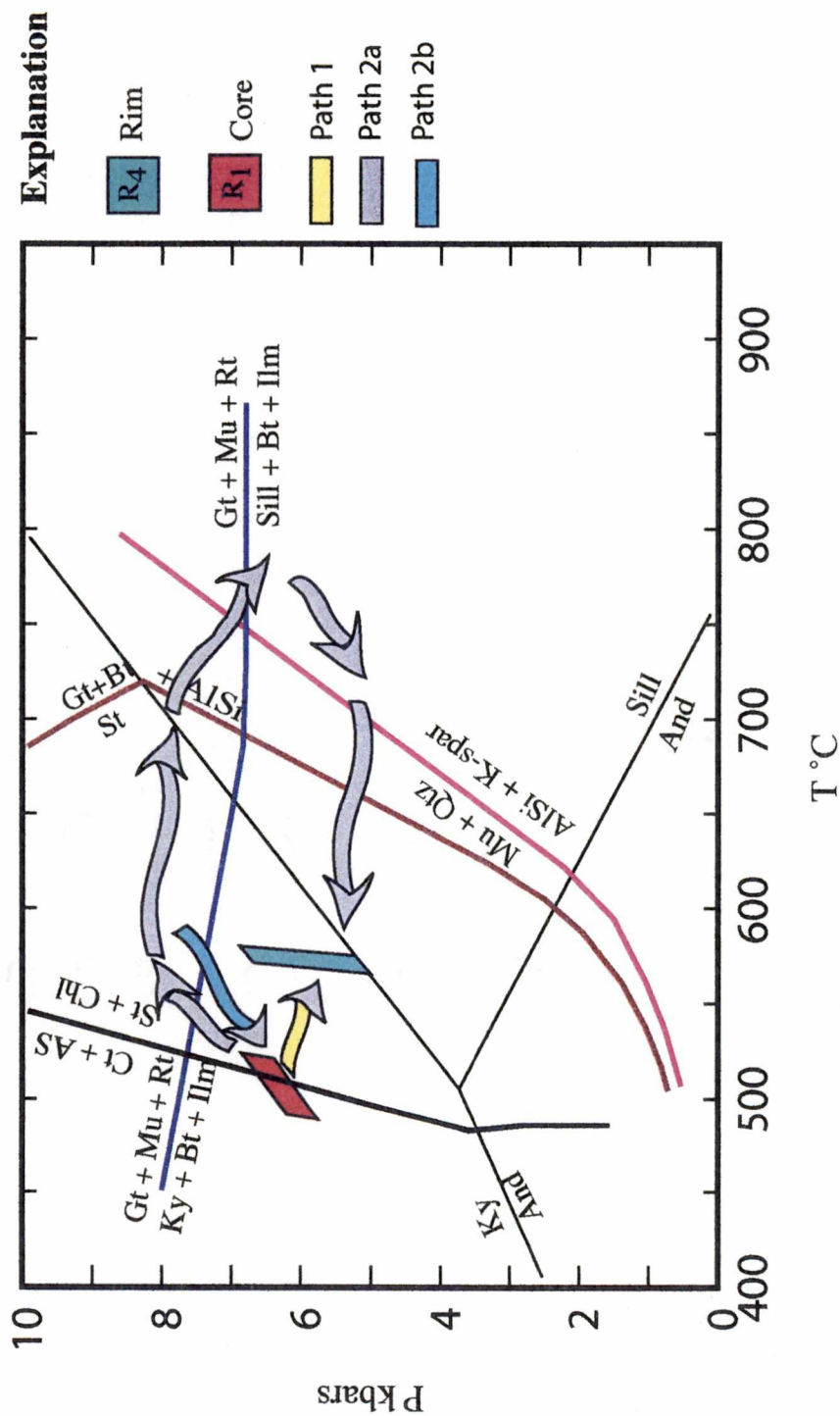


Figure 4.3 Relative P-T Paths a) Comparison between the core and the rim thermobarometry results for Sample 1 relative to the aluminum silicate stability fields and the regions of the garnet. The arrows represent the possible P - T paths of the garnet. Path 2a is a combination of path 2b with a resetting of the core of the garnet to later P-T conditions.

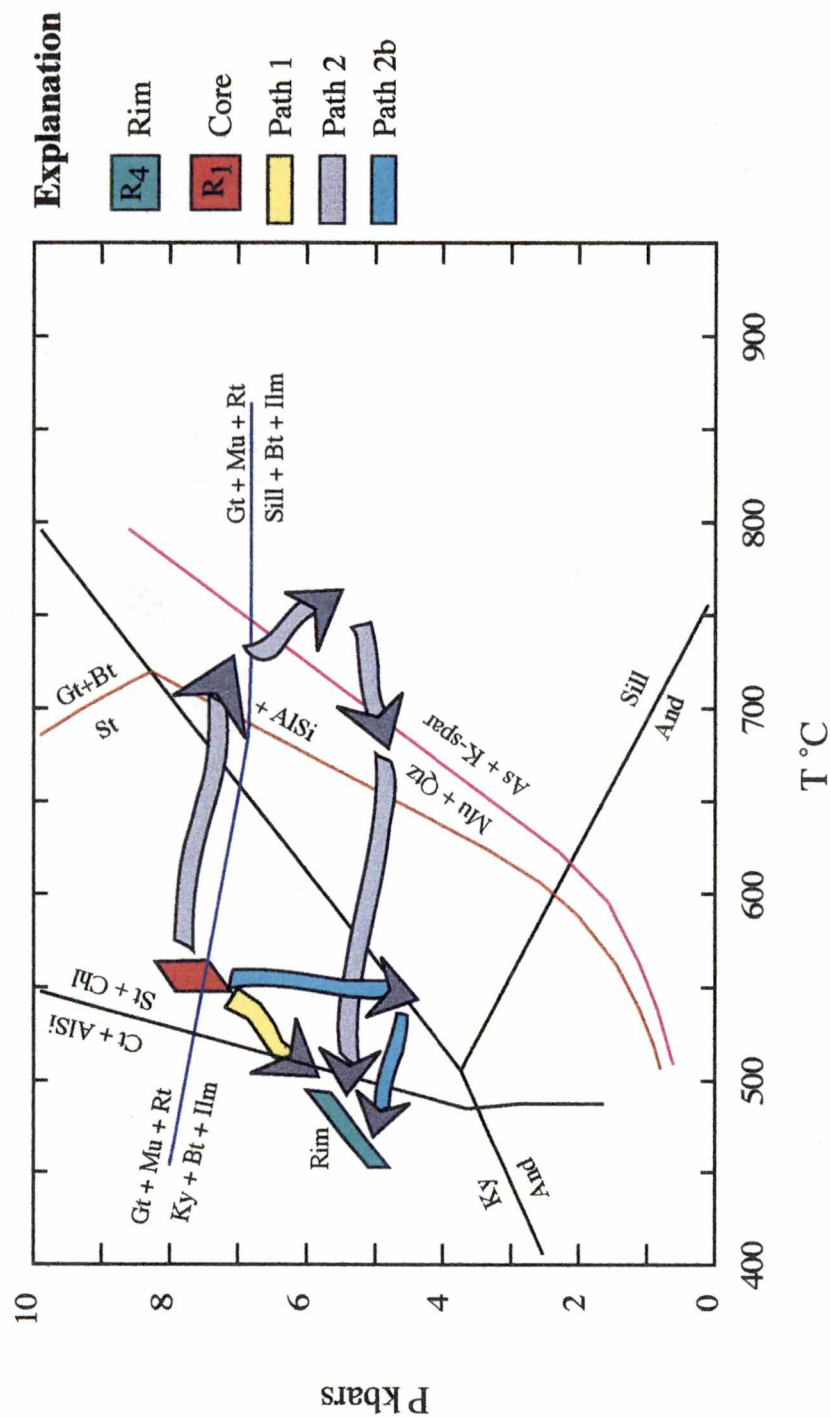


Figure 4.3 (continued) b) Three possible pressure - temperature paths for Sample 2. The arrows indicate the direction that the garnet might have taken along the path relative to the core and the rim thermobarometry.

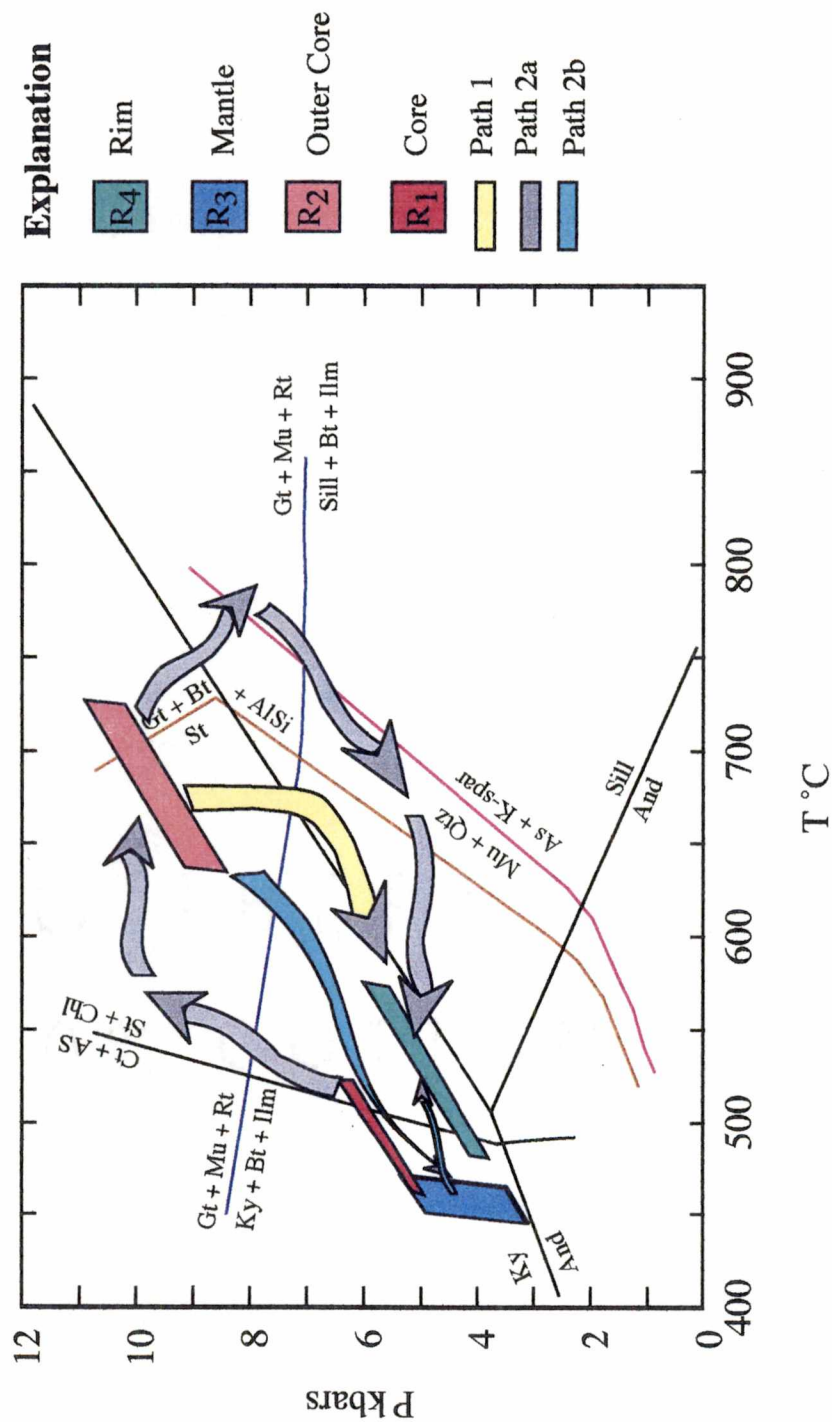


Figure 4.3 (continued) c) Three possible pressure-temperature paths for Sample 3. The arrows indicate the possible P-T paths for the growth history of the garnet relative to the thermobarometry.

then the path could be decompression and cooling until Region 3, then there would be a final increase in pressure and temperature through Region 4. Another route would be to bypass Region 3 and go to the rim conditions. This occurs by an isothermal decompression (path 1), then isobaric cooling.

Path 2a, for all samples, is a clockwise loop that is characteristic of an overthrust terrane (Spear, 1983; Crowley, 1991). This path follows an increase in pressure and temperature in the kyanite field, an isobaric heating then decompression with heating across the muscovite breakdown curve. The last stage of the loop follows a decompression and cooling through the sillimanite field until a final increase in pressure with cooling to the rim.

Path 2b is an alternate route that is based on the alteration of the core compositions in Samples 1 and 3. Once the path reaches the conditions of Region 2 of the garnet the garnet core re-equilibrates to the conditions of Regions 3 and 4.

Choosing an accurate P – T path is more complicated for the garnets in this study because of the amount of fracturing and the subsequent altering of the garnet's interior to later metamorphic conditions. Since all of the samples came from the same outcrop, they must have the same pressure temperature history and therefore they must have the same P-T path. Other methods that help to determine the relative P – T conditions are the mineral assemblages and the inclusions within minerals such as garnet. Inclusions of quartz, muscovite, K-feldspar, rutile, ilmenite, sillimanite, and in other studies staurolite (Labotka, personal communication) were found within the garnet. These minerals indicate that the pressure and temperature exceeded the

muscovite breakdown curve. For this reason the curved path (2a) is the more accurate indication of the evolution of the samples. Temperature and pressure calculations for the outer core (R_2) of the garnet indicate that pressures were in the kyanite and rutile stability fields and the temperatures were below the second sillimanite isograd. Potassium feldspar included in the garnet indicates that the thermal maximum occurred above the muscovite breakdown point. At some time during the rise to the thermal maximum, the pressure conditions decreased below the rutile breakdown reaction. The presence of euhedral sillimanite indicates that the kyanite – sillimanite boundary was also crossed. Temperature and pressure conditions had to decrease to the rim conditions. This retrograde metamorphism ended with the rim conditions in the kyanite field. The implications are that cooling had to occur fast enough so that sillimanite did not have time to break down completely to kyanite.

Pressure – Temperature Paths from Zoned Garnets

Compositionally zoned minerals such as garnet contain the evidence of their metamorphic history in their chemical zoning profiles (Spear, 1984; Jiang and Lasaga, 1990; Florence and Spear, 1991; Tucillo, 1990). The use of the garnet zoning profiles for P- T path calculations has been studied by Spear (1982), Spear and Selverstone (1983), and Spear and Peacock (1989). This method is based on the assumption that diffusion didn't alter the growth history of the garnet. The change in temperature (ΔT) and pressure (ΔP) are functions of the thermodynamic variance of an assemblage or consequently P or $T = f(x_1, x_2, \dots x_n)$.

Therefore, the total differentials of P and T are

$$dT = \sum (\partial T / \partial x_i)_{P, x_j \neq i} dx_i$$

$$dP = \sum (\partial P / \partial x_i)_{T, x_j \neq i} dx_i$$

where the differential dx_i is the change in the mineral composition along the chemical zoning profiles of the garnet. The slope of the lines represented by $(\partial P / \partial x_i)_{T, x_j \neq i}$ and $(\partial T / \partial x_i)_{P, x_j \neq i}$ can be calculated from the phase equilibria of the mineral assemblage (Spear, 1982; 1984; Spear and Selverstone, 1983b).

The GIBBS program uses the Gibbs differential method and was used in this study for the calculation of P – T paths from the zoning profiles of the garnets in the three samples. The Gibbs method uses a system of homogeneous linear equations that defines equilibrium in a mineral assemblage. The procedure takes the Jacobian matrix from the assemblage and calculates by finite difference the changes in a set of thermodynamic variables such as temperature (T), pressure (P), composition (X), and the number of moles of a phase (M). The program gives the user the freedom to choose which variables will be independent. The independent variables chosen for this study are X_{Alm} , X_{Gross} , X_{Spess} , X_{Pyr} , X_{An} .

The quantitative zoning profiles of Chapter 3 indicate places along the garnet's traverse where significant changes occur. It is important to the GIBBS method that the effects from retrograde reaction diffusion are limited so the data used for this study were taken from > 200 μm from the rim. Only the portions of the interior of the garnet where the slope of the zoning profiles were greater than zero and

the profiles had a typical growth zoning model described by Yardley (1977); Trzcinski (1977); Tucillo (1990); and Tracy and Robinson (1976) were used. Another factor that made modeling the samples difficult was the limited amounts of inclusions in Region 3 of the garnet.

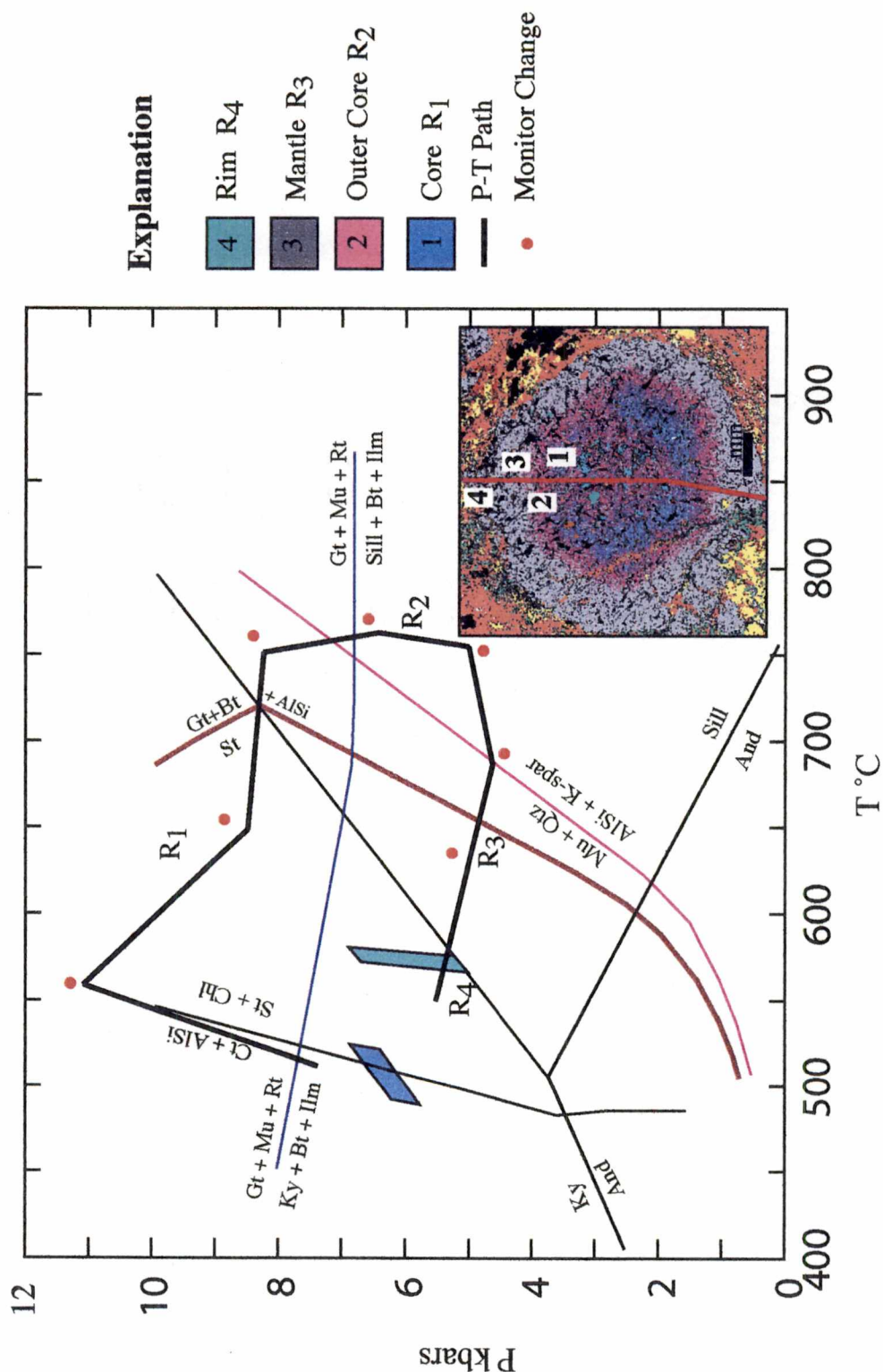
The system components consisted of the oxides SiO_2 , TiO_2 , Al_2O_3 , MgO , FeO , MnO , CaO , Na_2O , K_2O , and H_2O . A rim temperature calculated from thermobarometry was used with the starting mineral assemblage quartz + H_2O + muscovite + biotite + aluminum silicate + ilmenite + plagioclase and garnet. Because there are 8 phases and 10 system components, the variance is 4, and 4 monitors had to be chosen from X_{Alm} , X_{Gross} , X_{Spess} , X_{Pyr} , X_{An} . It is important to choose monitors that are linearly independent, and generally the 4 monitors X_{Alm} , X_{Gross} , X_{Spess} , and X_{An} were used.

The relationship between X_{An} and X_{Gross} wasn't linear. It was not possible to assume that the increments of change for anorthite would be even from the rim to the core of the garnet. Therefore, the increments for anorthite were not an average value that were calculated by the difference of the high values at the core minus the low values at the rim divided by the steps to create an evenly distributed ΔAn value along the P – T path. Fortunately, the program allows the user to back-step and to change the values of the monitors without resetting all of the parameters to the starting conditions. The backstepping gives the user the opportunity of adjusting the parameters to fit a path that is constrained by the temperature and pressure

calculations from the different regions of the garnet. It was also possible to make adjustments in the mineral assemblage along the path and minerals that were no longer stable could be changed for those minerals that were stable across a particular univariant curve. This gave me more options when the calculations reached a critical junction. I define a critical junction as a point in pressure and temperature space where the path that has been calculated is unrealistic given the knowledge of the mineral assemblage at that point in the garnet's traverse. These junctions usually occurred at univariant curves and they correspond with the kinks in the lines of the graphs in Figures 4.4a,b, and c.

Figures 4.4a-c show the calculated P – T paths and the thermobarometry for each sample. The regions of the garnet that are the approximate locations on the path are shown along with the corresponding micrograph. All the samples have a clockwise P – T loop that starts with an increase from the core P – T conditions from the rutile and kyanite stability fields. Samples 1 and 2 indicate that there was a pressure increase, while Sample 3 has an increase in pressure until Region 2 of the garnet is reached. Sample 1 increases past 10 kbars and then the pressure decreases until Region 2.

Sample 2 decreases in pressure isothermally, until the pressure and temperature values of Region 1 are reached. There was an isobaric heating followed by an increase in pressure from the core in Figure 4.4b and then there was another increase in temperature with a small increase in pressure until Region 2. All samples indicate a decrease in pressure as the heating continued past the muscovite breakdown



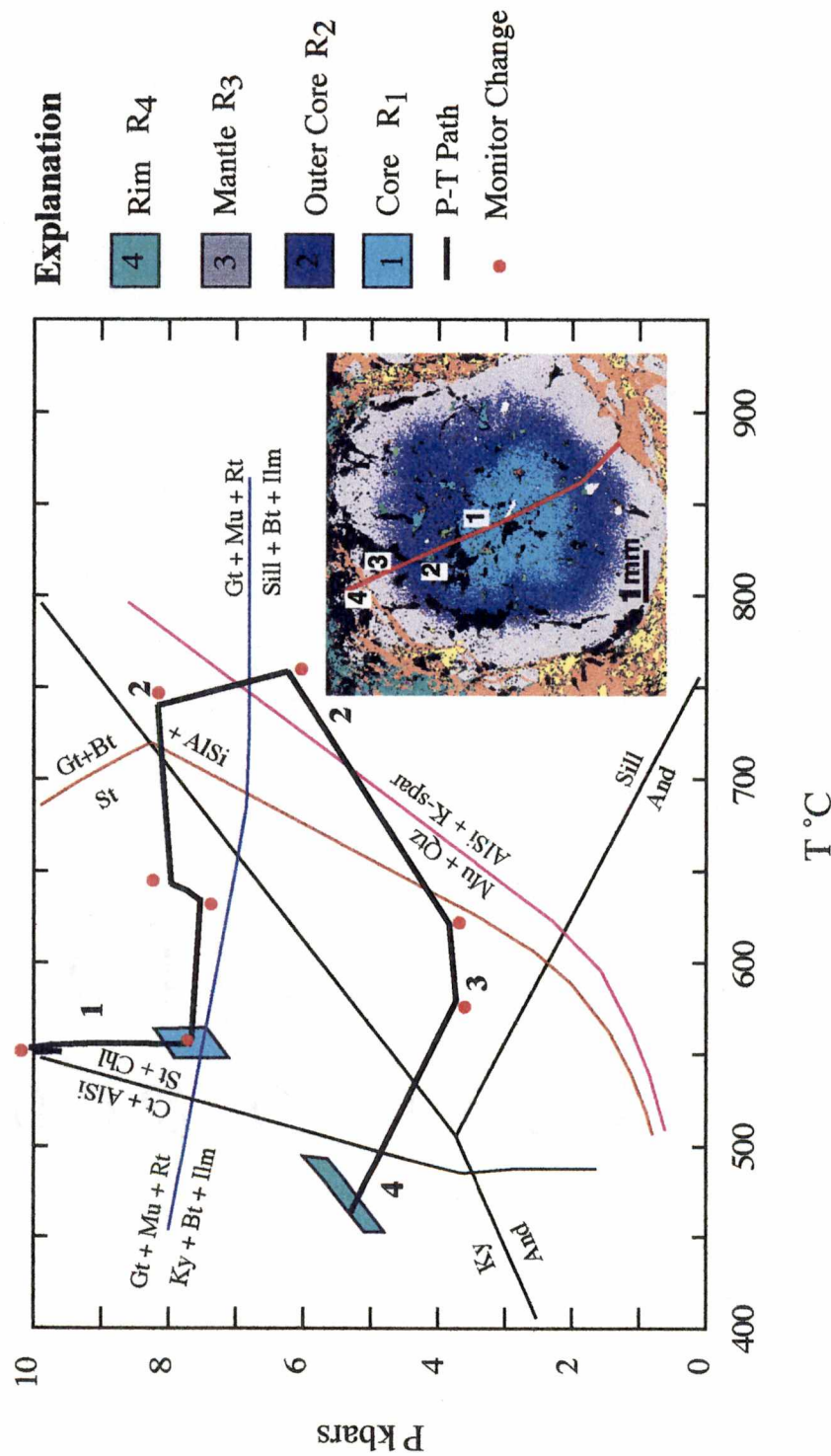


Figure 4.4 (continued) b) The pressure and temperature path for Sample 2 relative to the regions in the garnet. The Regions R₁-R₄ correspond to the numbers 1-4 on the micrograph. The path was calculated with the computer program *Gibbs 4.7* by Spear (1997). The red dots represent the approximate location where the monitors were changed.

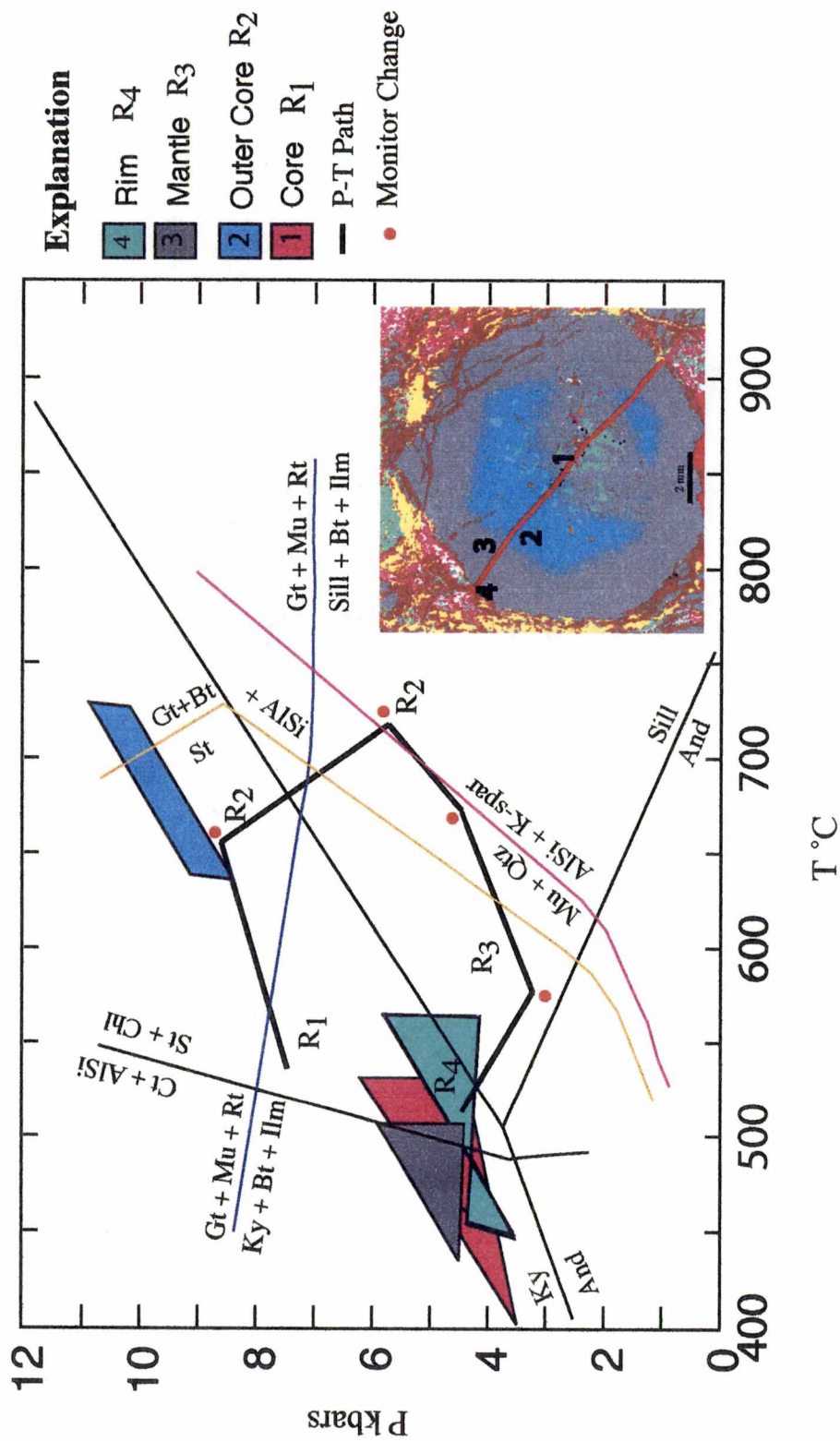
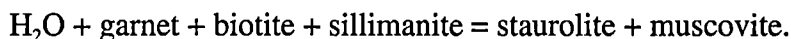


Figure 4.4 (continued) c) The pressure and temperature path for Sample 3 relative to the regions in the garnet. The Regions R₁-R₄ correspond to the numbers 1-4 on the micrograph. The path was calculated with the computer program *Gibbs 4.7* by Spear (1997). The red dots represent the approximate location where the monitors were changed.

point, and the pressure and temperature conditions were in the sillimanite + ilmenite field.

All the samples had a cooling and decompression period through Regions 2 and 3 across the univariant curve



There was an increase in pressure as the temperature decreased to the calculated rim conditions. The final pressure and temperature was back in the kyanite stability field.

The calculations of the P – T paths for the samples of this study were not straightforward. To calculate the paths, I had to guess the mineral assemblage, what minerals left the system, and at what point along the garnet zoning profile this occurred. Other useful indicator minerals such as staurolite were missing, so inferences about when the P – T path crossed from one mineral stability field to another is estimated. There were the critical junctions where the addition of a phase too soon or too big of a change in the monitor values caused the results to be either different from expected or totally illogical. It was at these junctions that the use of mineral inclusions within the garnet helped to limit the values of pressure and temperature that were calculated with the program to values that were consistent with the stability fields of the mineral assemblage.

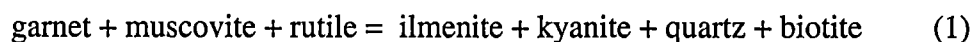
To calculate the P – T paths, the assumption that garnet growth was evenly distributed through P – T space seemed inappropriate. Are the samples of this study an isolated case or do growth and consumption of garnet occur in random, chaotic patterns?

V. Discussion and Conclusion

Discussion

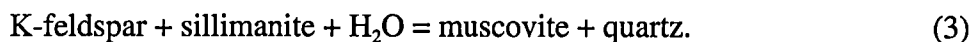
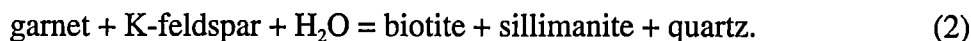
The study of the metamorphic conditions of the Cullowhee Gneiss must be a combination of analyses of the mineral assemblage in the matrix, the mineral inclusions in the garnet, and the analyses of the garnet zoning. The zoning profiles for the endmembers, almandine, pyrope, spessartine, and grossular contain clues to the metamorphic conditions that created the garnet. The zoning profiles for almandine and $\text{Fe}/(\text{Fe} + \text{Mg})$ indicate that temperatures were greater in the core than the outer regions of the garnet, while grossular indicates that the pressure was higher in the core of the garnet. The most recent clues to the history of the Cullowhee Gneiss are contained in the matrix and the outer regions of the garnet. Therefore, the discussion begins in the matrix and it will backtrack into the interior of the garnet.

The rocks for this study came from a single outcrop within the Cullowhee Gneiss. The mineral assemblage present in the matrix tells the story of the recent history of the rocks. The assemblage that makes up the Cullowhee Gneiss is muscovite + biotite + quartz + plagioclase + rutile + garnet + sillimanite $\pm$ staurolite $\pm$ kyanite. The textures of the minerals in the matrix indicate that prismatic sillimanite was stable, but garnet and kyanite were unstable. The presence of rutile in the matrix indicates that the pressure went above the rutile-ilmenite reaction:



The analyses from the zoning profiles of the garnet indicate that the mole fractions of spessartine and almandine are higher, while pyrope is lower at the rim than at the interior. The retrograde zoning at the rims is similar to that described by Tracy and

Robinson (1976) for the high-grade rocks from central Massachusetts. The anhedral shape of the garnets of this study indicates that the garnet was being consumed during the last stages of its history. Two reactions that consume K-feldspar are

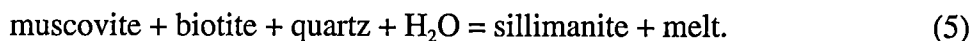
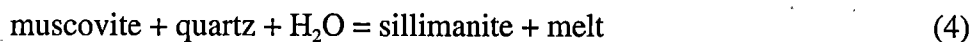


Reaction 2 consumes garnet and it produces a reverse zoning pattern that is depleted in Mg relative to Fe and Mn. This reaction might explain the presence of sillimanite in the rim of the garnet. Reaction 3 is the muscovite breakdown reaction that defines the second sillimanite isograd, and it produces prismatic sillimanite. Because there is not any K-feldspar visible in the matrix under the microscope, if reactions 2 and 3 occurred then all of the K-feldspar had to be consumed during the reaction. The reaction sequence that created the mineral assemblage that makes up the matrix of the samples had to have started in conditions that were favorable to garnet growth. The last stage of the garnet's history had to be in an environment that consumed the garnet.

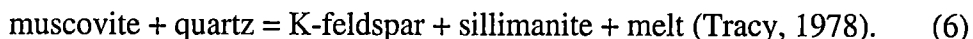
As the history of the garnet is traced back through R_3 into the interior of the garnet, the clues for the metamorphic conditions become harder to interpret. The zoning profiles indicate that the pressure and temperature conditions were greater through R_3 and R_2 of the garnet. Included minerals such as K-feldspar, rutile, ilmenite, and plagioclase with a high anorthite content indicate that higher pressures and temperatures existed than during the retrograde resorption of the garnet. Plagioclase inclusions become more anorthitic and the grossular content increases towards R_1 . This is another peculiarity about these samples because in a closed system an increase in grossular should be accompanied by a corresponding decrease in the anorthite content in plagioclase.

Therefore, either Ca was fractionated by the growing garnet and failed to maintain equilibrium with the matrix (Raleigh fractionation), or a melt phase was present and garnet was a refractory Ca-rich phase. The high anorthite content ($> \text{An}_{50}$) found within R_2 of these samples was reported in the plagioclase samples from granulite facies terranes such as Winding Stair Gap (Absher and McSween, 1985). This and the preceding observations lead to the question as to whether the Cullowhee Gneiss experienced partial melting?

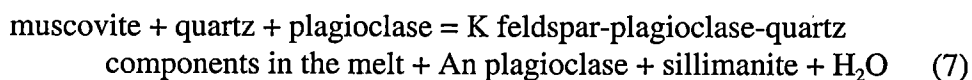
The included K-feldspar in the garnet, for these samples, indicates that at some point the temperatures went above the second sillimanite isograd. Thompson (1976) showed that the breakdown of muscovite could also have involved a melt:



Melting can continue with the breakdown of hydrous phases in the reaction that defines the second sillimanite isograd:



Another reaction could have produced melts at a lower temperature than Reaction 6. If plagioclase is present, then the temperature of anatexis decreases with a lower An content in the plagioclase. Winkler (1979) proposed the reaction



as an alternate process by which melting can occur. This reaction might account for the high anorthite content of the included plagioclase and consequently, as a result of the GASP equation, the garnet will also have a high Ca content.

The garnet zoning profiles indicate a complex metamorphic history. The core of the garnet formed in higher temperature and pressure conditions than the rim. The changes in the slopes of the profiles indicate changes in metamorphic conditions during the garnet's growth. The $\text{Fe}/(\text{Fe} + \text{Mg})$ values start at a maximum in R_1 and decrease in R_2 . This is an indication that the temperature decreased as the garnet grew. Sample 2 has a flattening of the profile from the end of R_2 to the beginning of R_3 . The flattened profile could be the result of homogenization or from growth at constant temperature. Homogenization from diffusion is not a reasonable explanation because the temperature was not high enough to effect the slow diffusion rate of calcium. There is another period of garnet growth during decreasing temperatures at the end of R_3 . This is followed by the retrograde resorption at the rim of the garnet.

All the garnets preserve three metamorphic periods in their zoning profiles. Sample 2 retained at least six changes in the metamorphic conditions. It is difficult to determine whether the high temperature and pressure recorded in the core were part of the same event or part of separate events. If the thermal maximum followed the initial high pressures without any garnet growth, then the high diffusion rates would have altered the zoning profiles and consequently the initial high-pressure part of the path would have been erased.

The $P - T$ paths that were calculated from the zoning profiles of the garnets in this study retained the high-pressure part of the history. Samples 1 and 2 indicate that there was a high-pressure metamorphic event followed by a decrease in pressure, and then there was an increase in pressure as the temperature increased. The thermal maximum

for all samples occurred after the pressure decreased below the ilmenite-rutile reaction curve. This type of path is typical of rocks that were part of an overthrust terrane.

The P – T models of Spear and Selverstone (1983, 1984), England and Thompson (1984), and Crowley (1991) indicate that the shape of the clockwise loop that the path makes also indicates whether the rocks are part of the upper or the lower plates in a thrust sequence. There is a transfer of heat by conduction from the bottom of the top rock layers into the top of the rocks on the bottom (Crowley, 1991).

If the Cullowhee Gneiss was the bottom plate, then the Otto Formation should be the upper plate. The P – T paths for the top plate should record an initial cooling and then a heating period. Unless the uplift rate is very slow, the thermometers should record temperatures similar to those at the time of thrusting (Crowley, 1991). The P – T paths calculated by Davidson (1995) for the Otto Formation are not complete and therefore inconclusive. The temperature and pressure values for the Otto Formation have a high initial temperature and pressure with a maximum value of 720 °C and 8.0 kbars. The calculated initial temperature and pressure values are suspect because garnet core and matrix minerals were used. The pressure values using inclusions in the garnet are 6.1 – 7.0 kbars, and the rim values are 4.1 – 8.0 kbars. If the Otto Formation were structurally on top of the Cullowhee Gneiss, the pressure values would be smaller than those for the Cullowhee Gneiss.

The timing of the metamorphic episodes of the Cullowhee Gneiss relative to the Grenville, Taconian, Acadian, and Alleghanian orogenies can only be estimated by the dating on rocks from other Eastern Blue Ridge locations. Miller and Hatcher (1998) used high-resolution ion microprobe dating of monazite and zircon from plutons in the Eastern

Blue Ridge to obtain an age of the high temperature magmatic event at 480 Ma (Taconian) and an age of the Acadian Orogeny at 380 Ma. The Taconian age is close to the age proposed by Butler (1979) and is the same as that proposed by Kish (1982). There is agreement by Absher and McSween (1985), Eckert (1984, 1989), and McSween and Hatcher (1985) that the Taconian Orogeny was the major thermal event in the Eastern Blue Ridge. The high temperature values for the samples of this study coincide with the Taconian Orogeny. There is an overprinting of an earlier high pressure and lower temperature event by the high thermal event, and part of the P – T paths of Samples 1 and 2 of this study might be remnant from the earlier event. Correlating the early history of the Cullowhee Gneiss with the dates from the cores of the zircons in the study of Miller and Hatcher (1998) would place the date of the high-pressure metamorphism in the Grenville Orogeny. The retrograde path of the garnet through Region 3 could have occurred during the late Paleozoic time and the retrograde rims of the garnet were formed during the Alleghanian Orogeny.

Hatcher and Butler (1979) distinguished at least six deformational events in the eastern Blue Ridge. Davidson (1995) identified at least three folding events and three foliations in the Cullowhee Gneiss. Inclusions of sillimanite in the rims of the garnet are parallel to the matrix foliation and are synkinematic (Davidson, 1995). Sillimanite in the garnet rims must have grown during the retrograde metamorphic event. The calcite inclusion trails crosscut the rim and R_3 and part of R_2 and had to have followed the last growth of the garnet.

Conclusion

The Cullowhee Gneiss had a polymetamorphic history. The first metamorphism was overprinted by a second metamorphism with the pressures and temperatures recorded in Regions 1 and 2. Sample 2 had the high values of 530 – 610 °C and 7.1 – 8.1 kbars in R_1 . Sample 3 had the highest temperatures and pressures of 590 - 730 °C and 8.0 – 9.0 kbars in Region 2. The third metamorphic event was at lower temperature and pressure conditions and created the outer shell of the garnet (R_3). The final metamorphism was retrograde and produced R_4 . Temperature and pressure values for Regions 3 and 4 are lower at 450 – 575 °C and 5.0 – 6.8 kbars.

The change in the slope of the lines of the garnet zoning profiles for these samples reflect the changes in the metamorphic conditions. There was a homogenization of the profiles by diffusion in the center of the garnet (R_1). The garnet grew big enough not to be reset at the lower temperatures of R_3 , and R_4 . The decrease in the values of Mn and Ca from core to rim and the increase in Mg were the result of garnet growth, while the increase in Mn, the decrease in Mg, and the increase in Fe at the rim are indicative of retrograde diffusion.

This study consisted of taking the qualitative images from the x-ray scans of three garnet samples and relating the images to the quantitative data from the same samples. The qualitative images indicate that the garnets were fractured in the interior. The fractures were filled with garnet that grew at a different temperature and pressure and this gives a false interpretation of the garnet's history.

The combined evidence from both the quantitative and qualitative analyses was used to investigate the pressure and temperature history of the outcrop. The included

minerals rutile and ilmenite in the garnet and the relic kyanite in the matrix indicate that the Cullowhee Gneiss had an early high-pressure history. Prismatic sillimanite in the matrix and the needles of sillimanite in the garnet indicate at least two periods of sillimanite growth. Included K-feldspar indicates that temperatures were above the muscovite breakdown curve. The high aluminum content, the migmatization, and the high anorthite content of the included plagioclase indicate that the Cullowhee Gneiss experienced partial melting.

Calculated P-T paths from the garnet zoning profiles produced clockwise paths that are typical of overthrust terranes. All three of the samples have paths that exceed the muscovite breakdown reaction curve, but Samples 1 and 2 retained a high-pressure part of the loop that was part of an earlier metamorphism.

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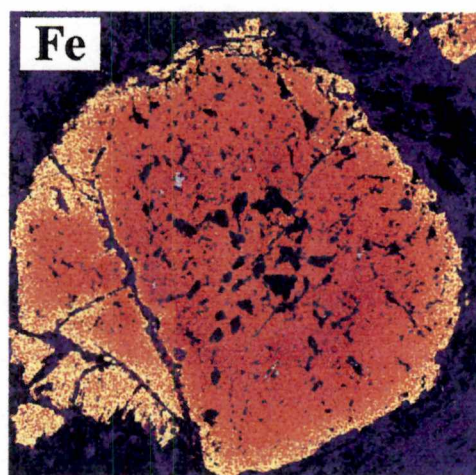
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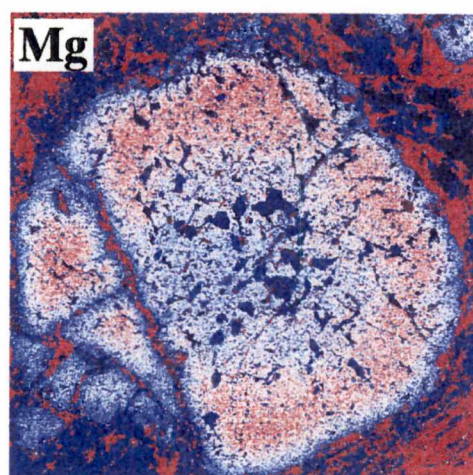
APPENDICES

Appendix 1a: Qualitative X-ray Images of the Elements for Sample 1

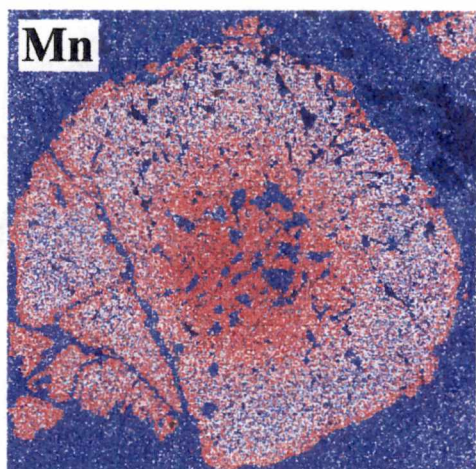
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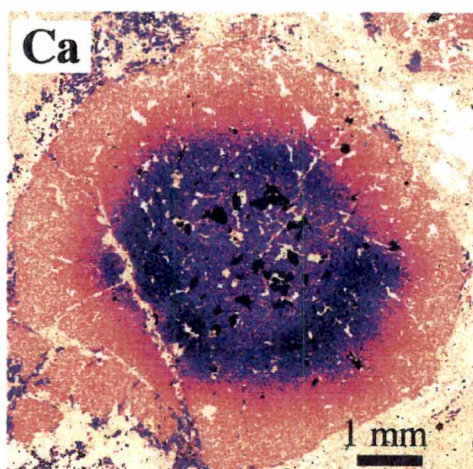
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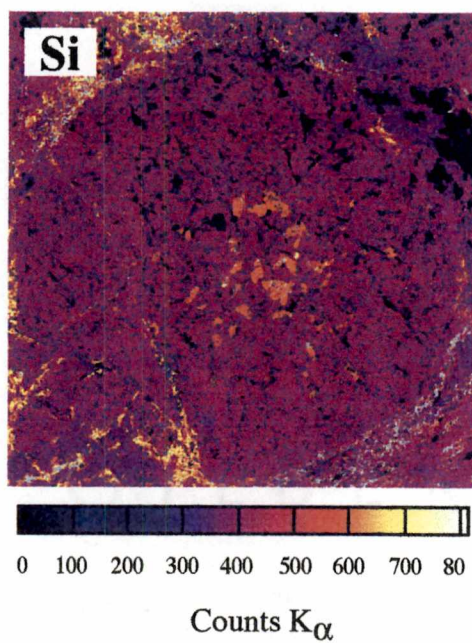
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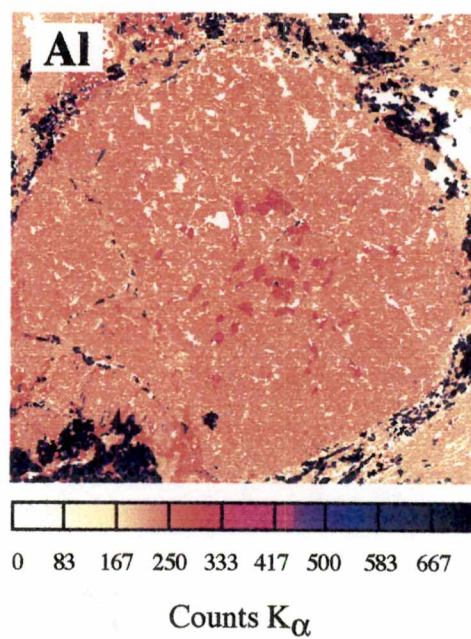
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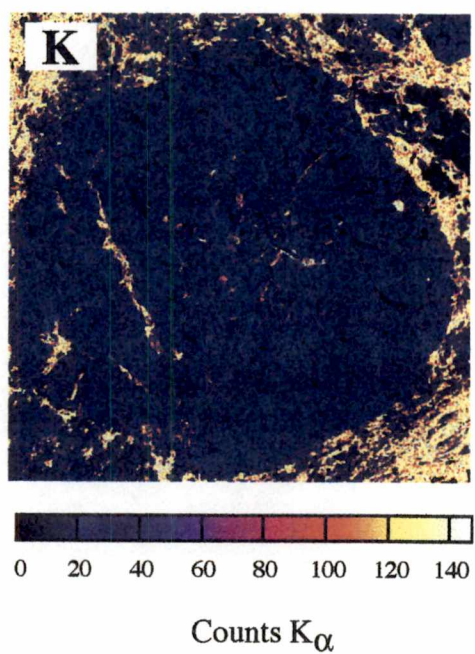
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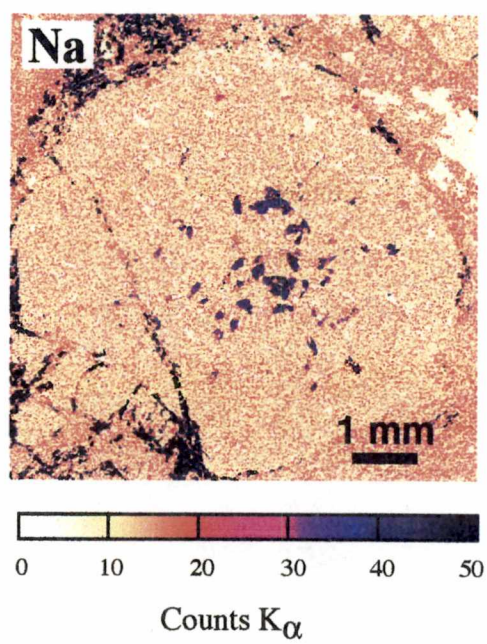
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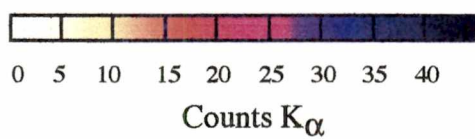
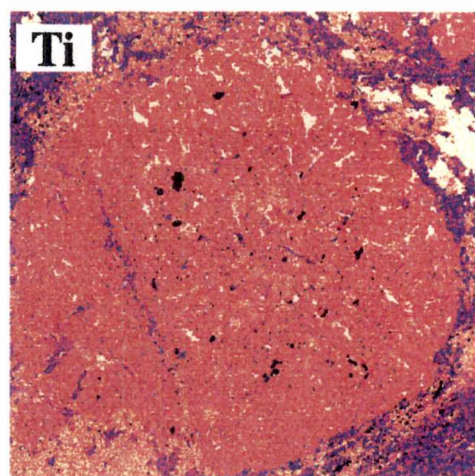
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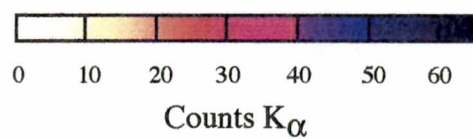
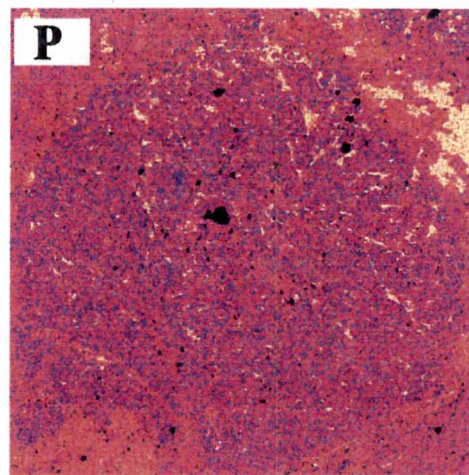
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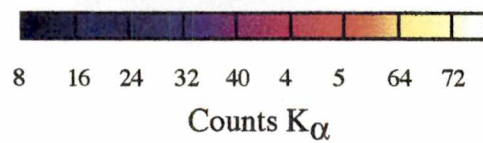
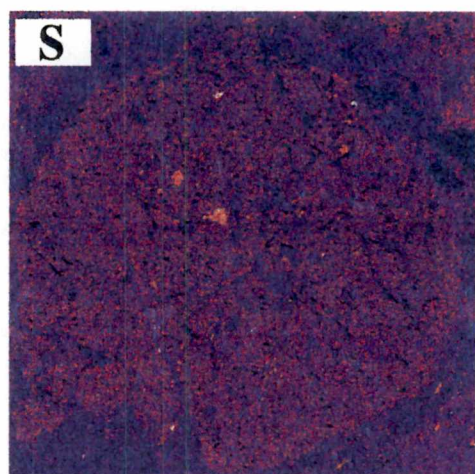
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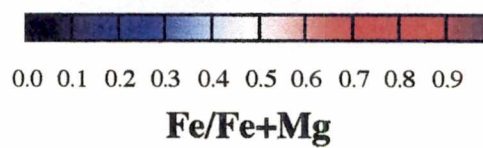
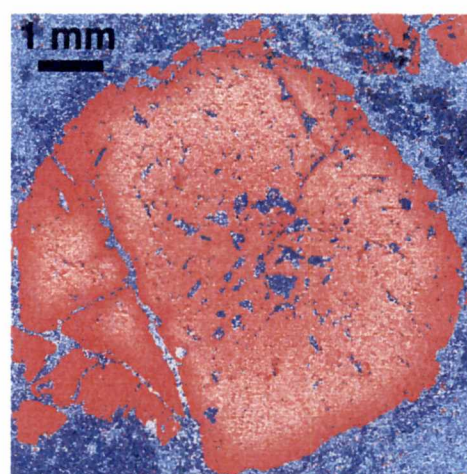
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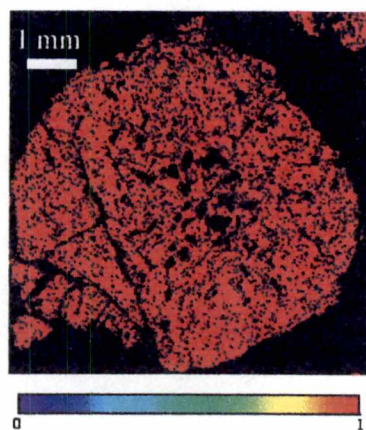
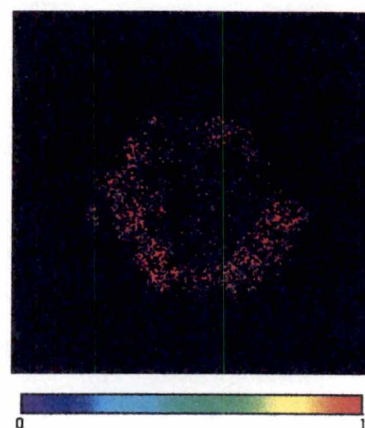
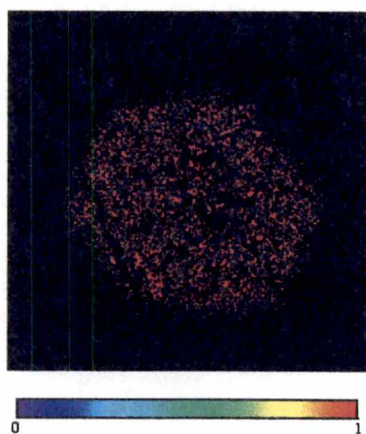
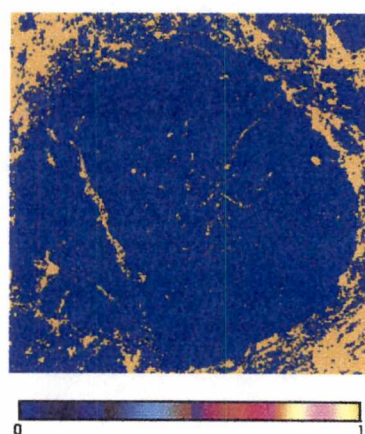
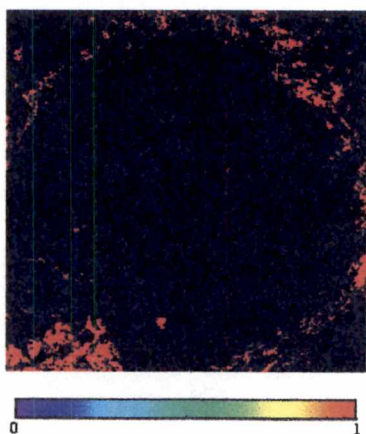
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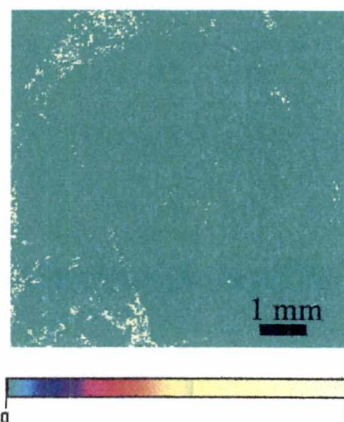
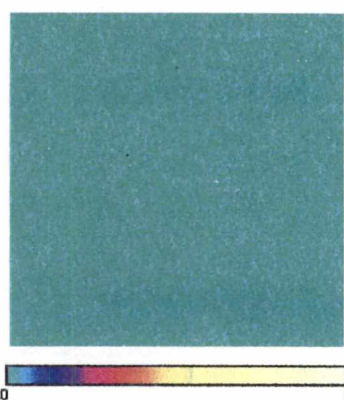
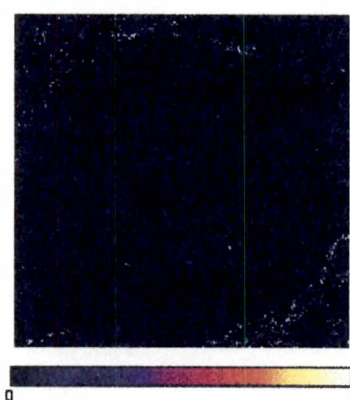
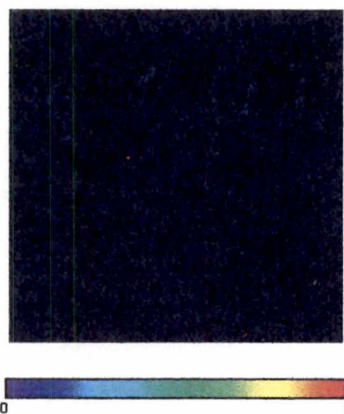
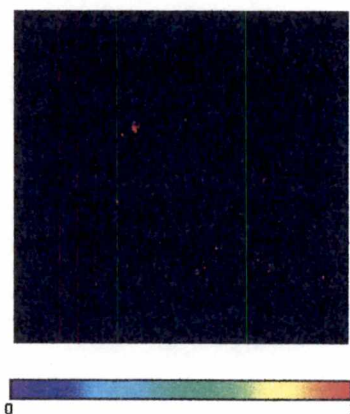


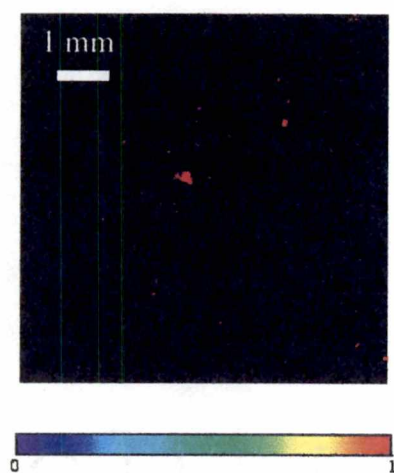
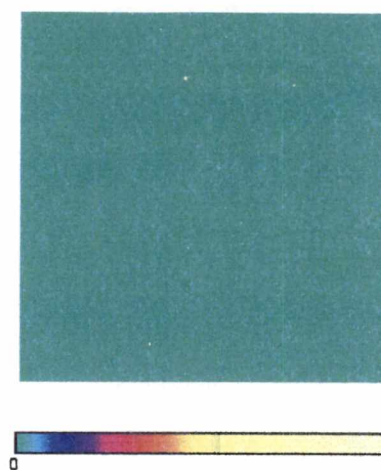
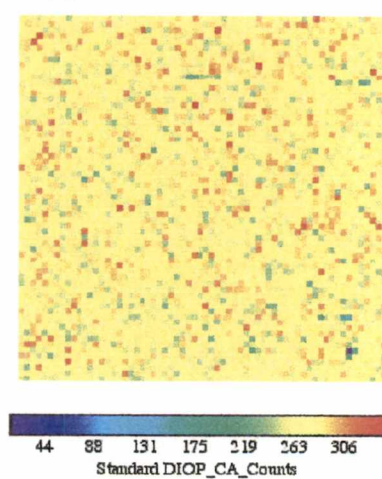
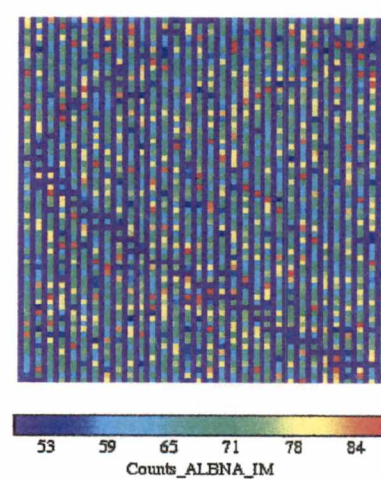
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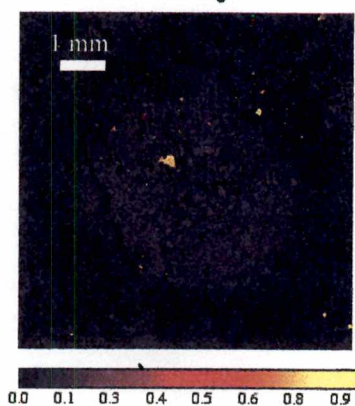
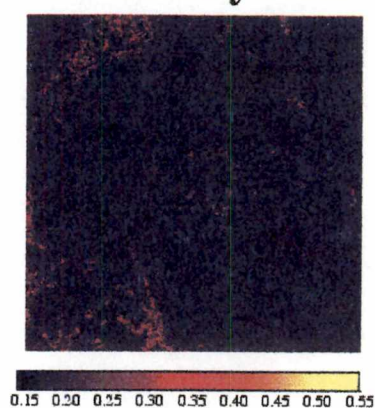
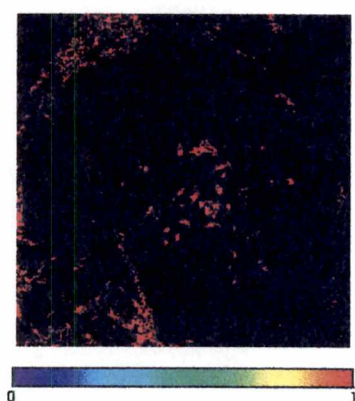
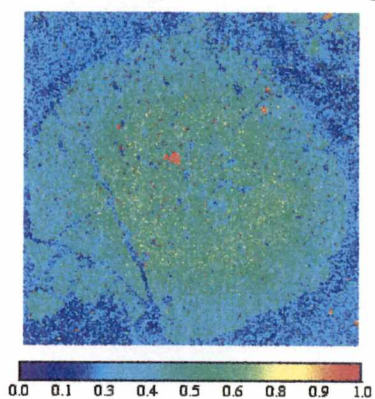
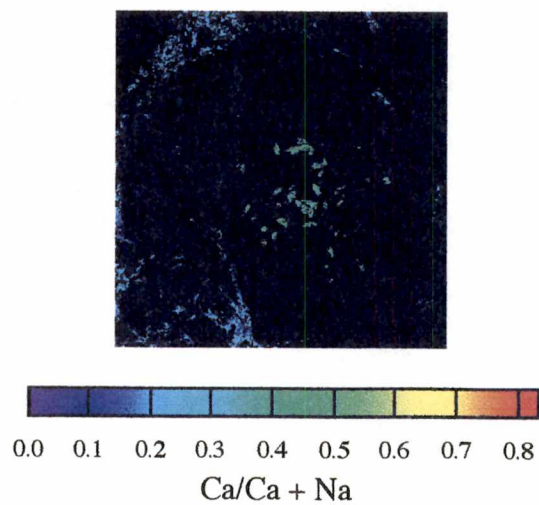


Appendix 1b: Qualitative Masks of the Minerals for Sample 1

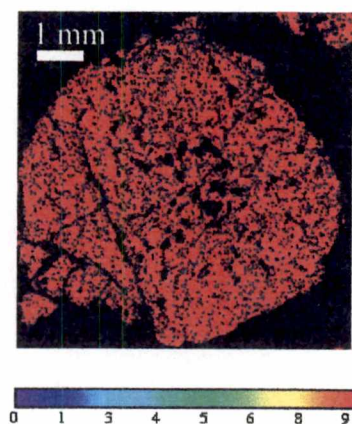
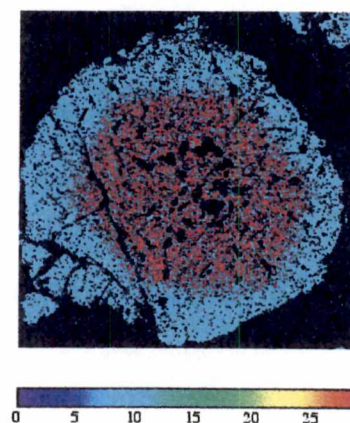
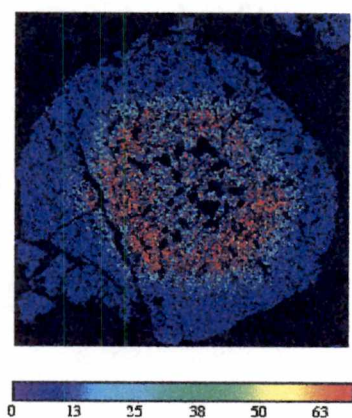
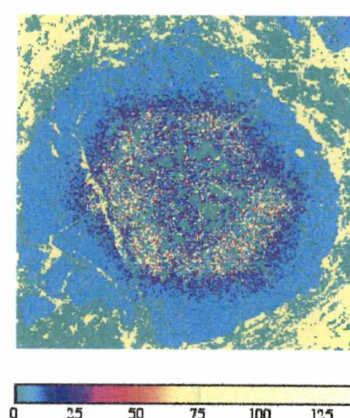
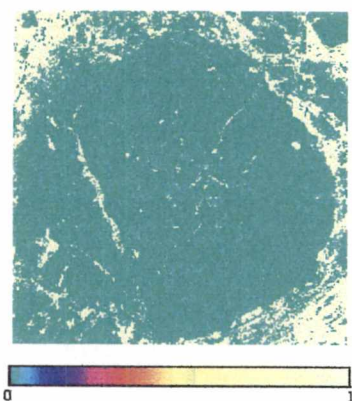
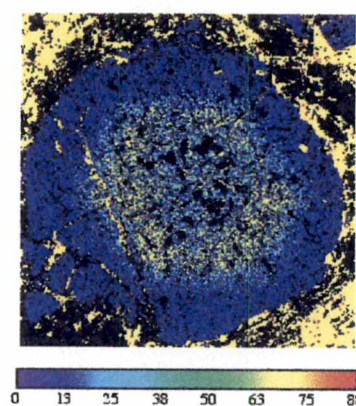
a.) Garnet Mask**b.) Garnet Medium Ca Mask****c.) Garnet High Ca Mask****d.) Biotite Mask****e.) Al Silicate Mask****f.) Muscovite Mask**

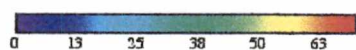
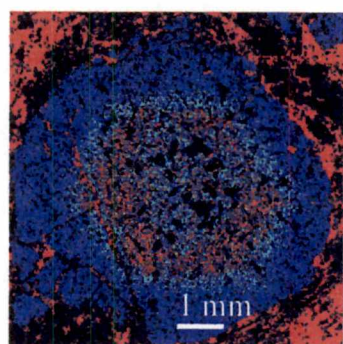
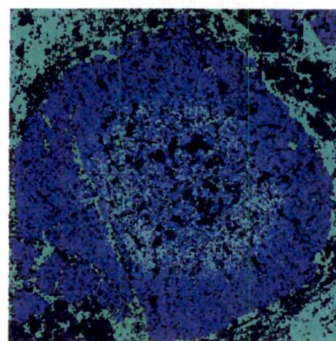
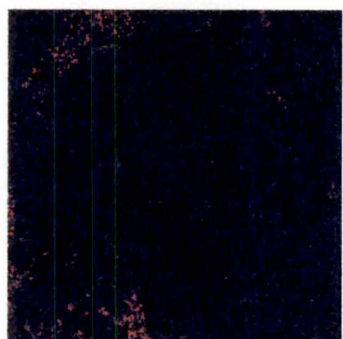
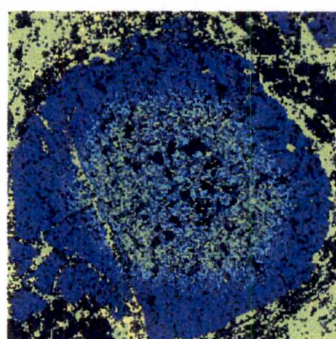
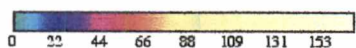
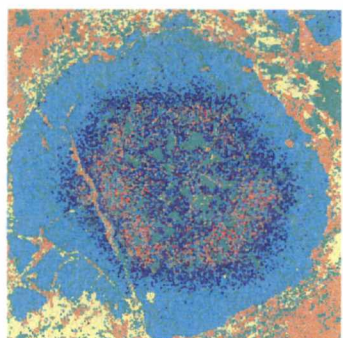
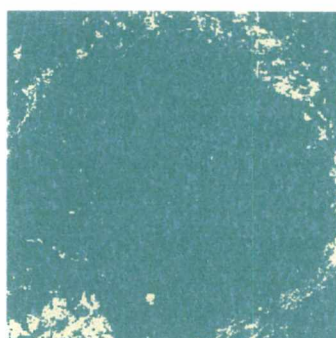
g.) Plagioclase Na Mask**h.) Plagioclase Ca Mask****i.) K-feldspar Mask****j.) Quartz Mask****k.) Rutile Mask****l.) Ilmenite Mask**

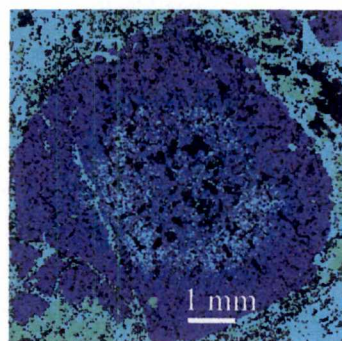
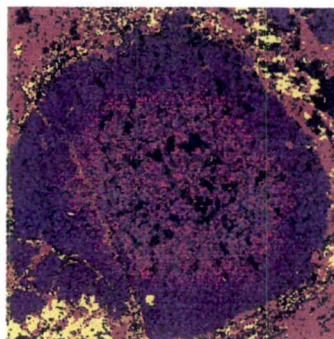
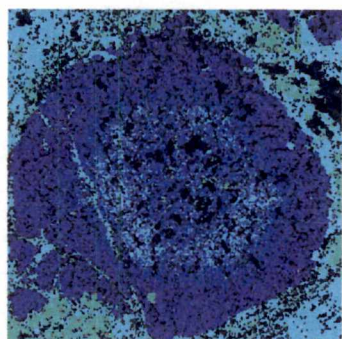
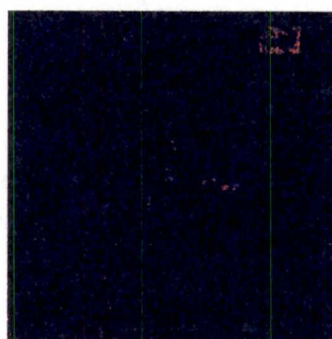
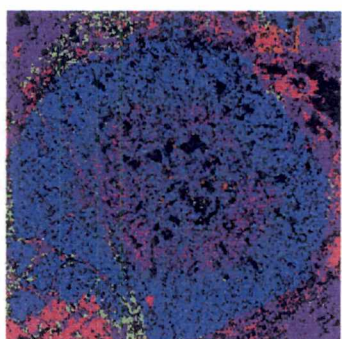
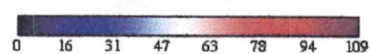
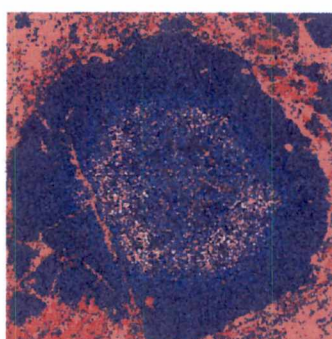
m.) Apatite Mask**n.) Monazite Mask****o.) Diop Standard****p.) Alb Standard**

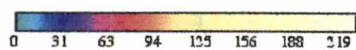
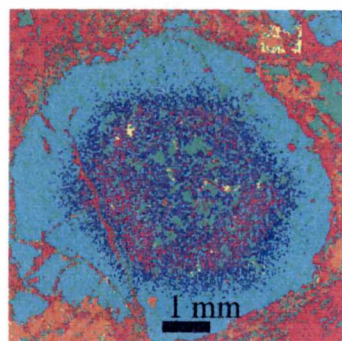
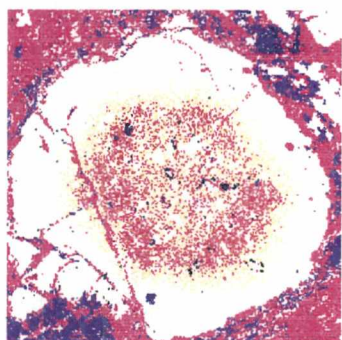
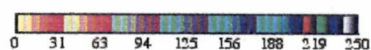
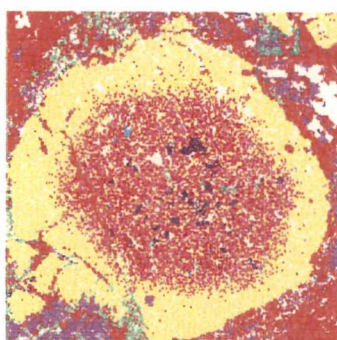
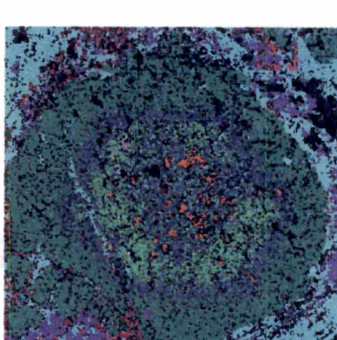
q.) Ca Intensity Mask**r.) Na Intensity Mask****s.) Anorthite Mask****t.) Ca Semi-quant Intensity****u.) Plagioclase An Range**

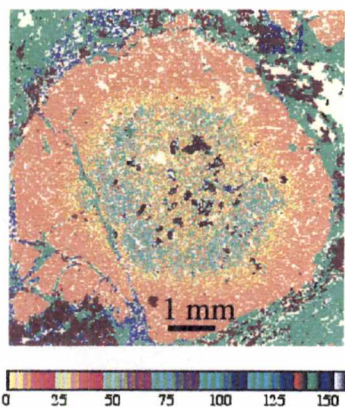
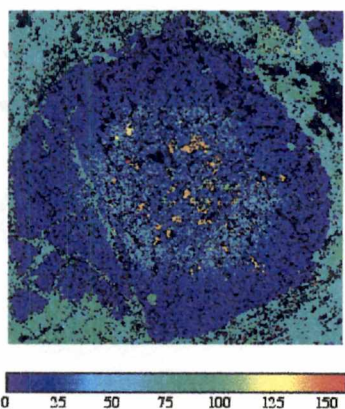
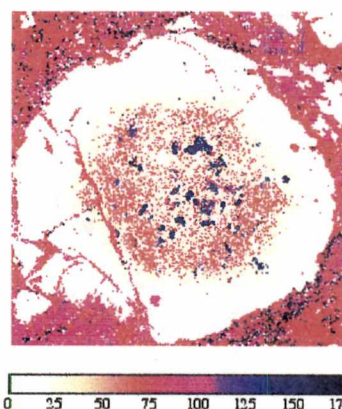
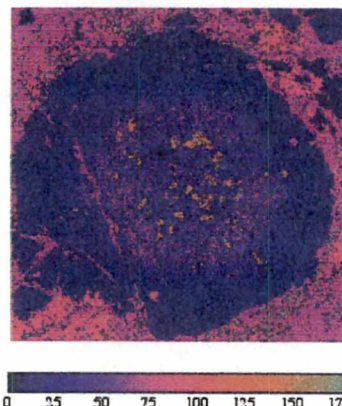
Appendix 1c: Micrographs for Sample 1

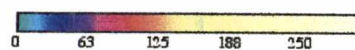
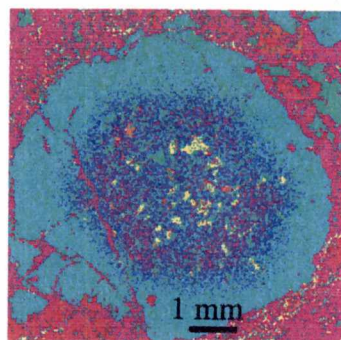
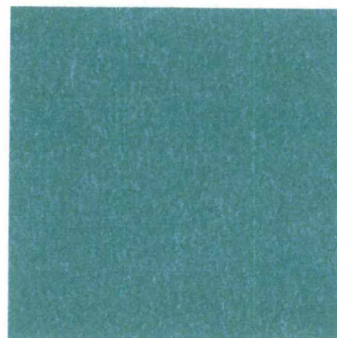
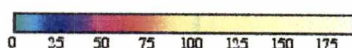
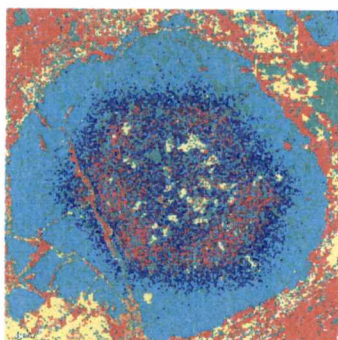
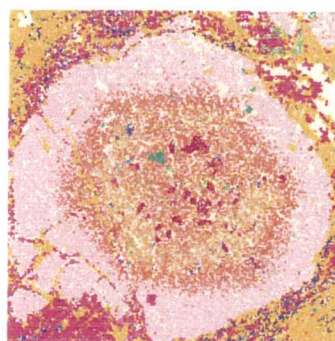
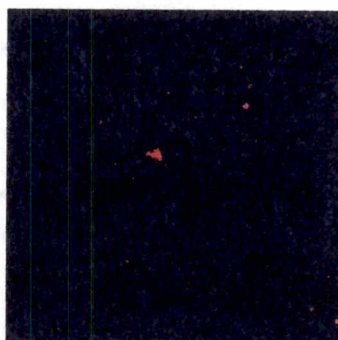
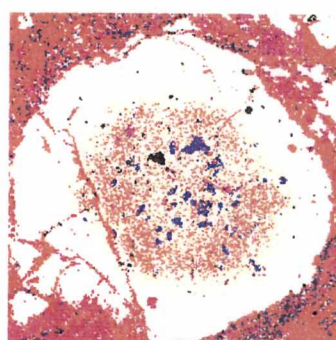
a.) Micrograph 1**b.) Micrograph 2****c.) Micrograph 3****d.) Micrograph 4****e.) Micrograph 4a****f.) Micrograph 4b**

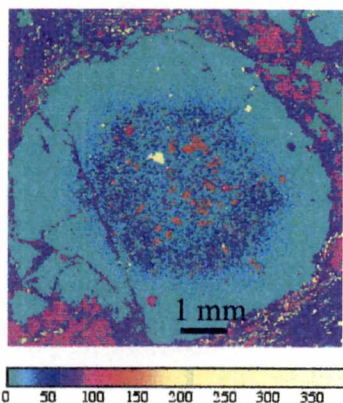
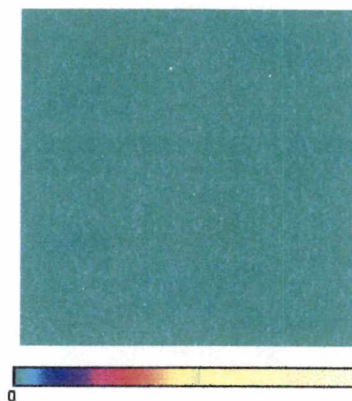
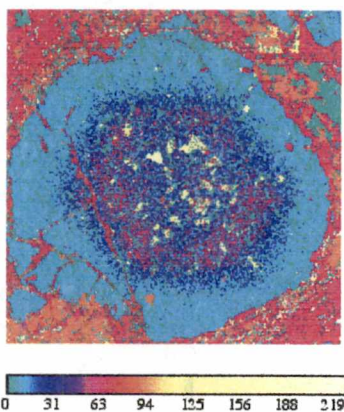
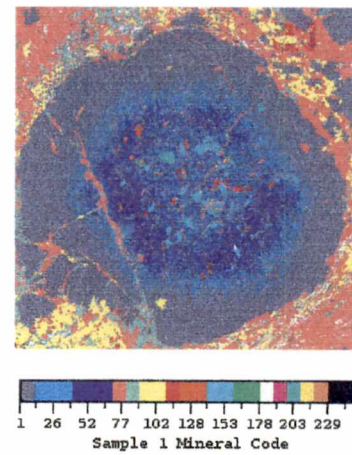
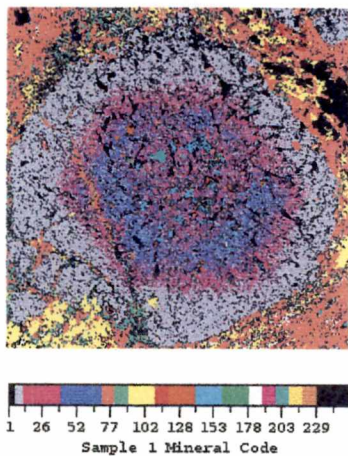
g.) Micrograph 4c**h.) Micrograph 5****i.) Micrograph 5a****j.) Micrograph 5b****k.) Micrograph 6****l.) Micrograph 6a**

m.) Micrograph 6b**n.) Micrograph 6c****o.) Micrograph 7****p.) Micrograph 7a****q.) Micrograph 7b****r.) Micrograph 7c**

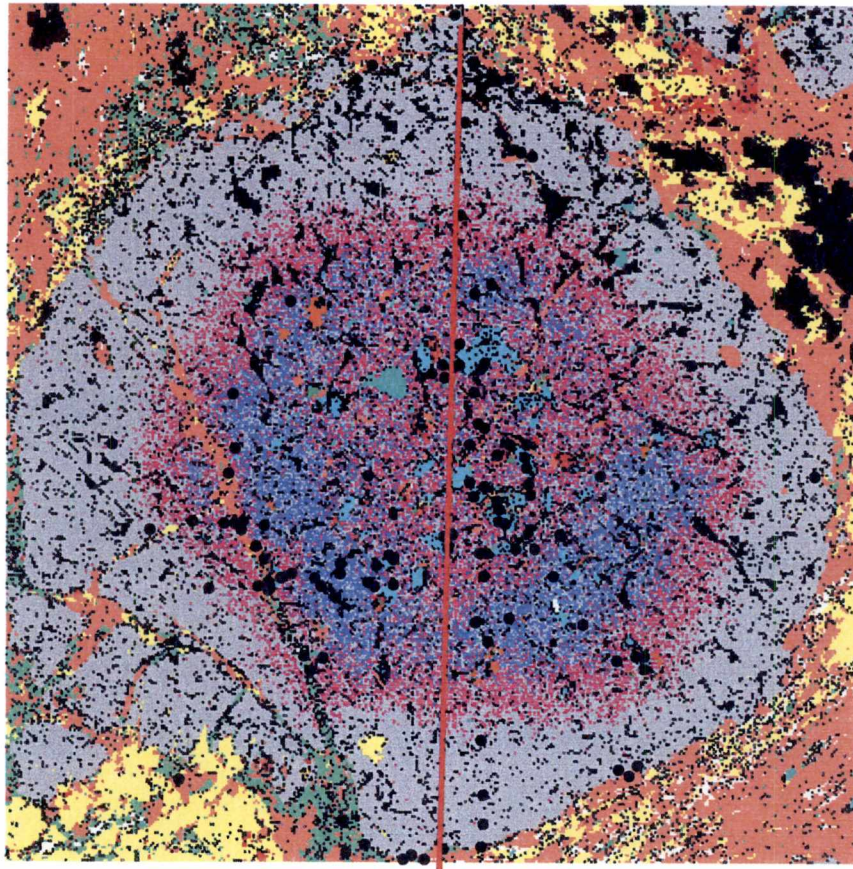
s.) Micrograph 8**t.) Micrograph 8a****u.) Micrograph 8b****v.) Micrograph 9****w.) Micrograph 9a****x.) Micrograph 9b**

y.) Micrograph 10**z.) Micrograph 10a****aa.) Micrograph 10b****bb.) Micrograph 11****cc.) Micrograph 11a****dd.) Micrograph 11b**

ee.) Micrograph12**ff.) Micrograph 12a****gg.) Micrograph 12b****hh.) Micrograph 13****ii.) Micrograph13a****jj.) Micrograph 13b**

kk.) Micrograph 14**ll.) Micrograph14a****mm.) Micrograph 14b****nn.) Micrograph 14b2****oo.) Micrograph 14b4**

pp.) **Sample 1 Final Micrograph and Color Code**



Explanation

 1 mm		 Traverse	
	Garnet: Low Ca		Quartz
	Garnet: Med Ca		Aluminum Silicate
	Garnet: Hi Ca		Plagioclase: An 23
	Biotite		Plagioclase: An 45
	Muscovite		Ilmenite
	Quantitative Points		Rutile

Appendix 1d: Micrograph Computer Code for Sample 1

Sample 1 Mineral Masks

The Mineral Masks for each Sample were pieced together in the computer program *Transfom PPC 3.4*. To make the masks, the appropriate elemental maps were opened and combinations of intensity levels from different elements masked out the unwanted portions of the entire qualitative map. The only part of the qualitative map that was left to view was the desired mineral.

GE = $\geq$; GT = $>$; LE = $\leq$; LT = $<$; S₁ = Sample 1

Garnet_Fe_Mask = GE Mask (S₁_Fe_Data, 85) * GT (S₁_Al_Data, 180).

Garnet_MED_Ca_Mask = GE (S₁_Al_Data, 220) * GE (S₁_Ca_Data, 44)
* LT (Na_Data, 15).

Garnet_High_Ca_Mask = GE (S₁_Al_Data, 220) * GE (S₁_Ca_Data, 68)
* LT (Na_Data, 15).

Biotite_Mask = GE (S₁_Al_Data, 100) * GT (S₁_Mg_Data, 50)
* GT (S₁_K_Data, 44).

Muscovite_Mask = GT (S₁_K_Data, 40) * LT (S₁_Mg_Data, 40)
* GE (S₁_AL_Data, 130).

Al_Silicate_Mask = GT (S₁_Al_Data, 490) * GE (S₁_Si_Data, 250).

Quartz_Mask = GT (S₁_Si_Data, 900)*LE (Al_Data, 50).

Apatite_Mask = GT (S₁_P_Data, 50) * GT (S₁_Ca_Data, 300).

Monazite_Mask = GT (S₁_P_Data, 65) * LE (S₁_Ca_Data, 55)*
GT (Ca_Data, 40).

Rutile_Mask = GE (S₁_Ti_Data, 500) * LE (S₁_Fe_Data, 30).

Ilmenite_Mask = GT (S₁_Fe_Data, 120) * GT (S₁_Ti_Data, 50).

Plagioclase_Na_Mask = GE (S₁_Al_Data, 250) * GE (S₁_Na_Data, 40)
* LT (Ca_Data, 95).

$$\text{Plagioclase_Ca_Mask} = \text{GE}(\text{S1_Al_Data}, 260) * \text{GE}(\text{S1_Ca_Data}, 100) \\ * \text{LE}(\text{Na_Data}, 50).$$
$$\text{K_Feldspar_Mask} = \text{GE}(\text{S1_K_Data}, 165) * \text{LE}(\text{S1_Na_Data}, 40).$$

Pt_Mask = A Matrix 512 X 512 with 1 representing the quantitative points.

S₁ Micrograph Reconstruction Code

All Micrographs were pieced together in the program

Transform PPC 3.4. Since TransforS1M only codes from 1 - 254 the counts had to be scaled to this range.

S₁M# = Sample1 Micrograph number.

$$S_{M1} = 20 * Gt_Mask + 40 * Garnet_Ca_Mask.$$
$$S_1M\ 1a = LE\ (S_1M\ 1, 60)$$
$$S_1M1b = S1M1 * S_1M1a$$
$$S_1M_2 = S_1M_{1b} + (80 * Bt_Mask)$$
$$S_1M_{2a} = LT(S_1M_2, 100) * GE(S_1M_2, 80)$$
$$S_1M\ 2b = S_1M\ 1b + (S_1M\ 2a * S_1M\ 2)$$
$$S_1M\ 3 = S_1M\ 2b + (100 * Na_Plag_Mask)$$
$$S_1M\ 3a = LT(S_1M\ 3, 120) * GE(S_1M\ 3, 100)$$
$$S_1M\ 3b = S_1M\ 2b + (S_1M\ 3a * S_1M\ 3)$$
$$S_iM\ 4 = S_iM\ 3b + (120 * Sill_Mask)$$
$$S_1M\ 4a = LT(S_1M\ 4, 140) * GE(S_1M\ 4, 120)$$
$$S_1M\ 4b = S_1M\ 3b + (S_1M\ 4a * S_1M\ 4)$$
$$S_1M_5 = S_1M_{4b} + (140 * Musc_Mask)$$
$$S_1M\ 5a = LT(S_1M\ 5, 160) * GE(S_1M\ 5, 140)$$
$$S_1M\ 5b = S_1M\ 4b + (S_1M\ 5a * S_1M\ 5)$$
$$S_1M_6 = S_1M_{5b} + (160 * II \ S_1M_Mask)$$
$$S_1M\ 6a = LT(S_1M\ 6, 180) * GE(S_1M\ 6, 160)$$
$$S_1M\ 6b = S_1M\ 5b + (S_1M\ 6a * S_1M\ 6)$$
$$S_{,M} 7 = S_{,M} 6b + (180 * Ca_Plag_Mask)$$
$$S_1M\ 7a = LT(S_1M\ 7, 200) * GE(S_1M\ 7, 180)$$
$$S_1M\ 7b = S_1M\ 6b + (S_1M\ 7a * S_1M\ 7)$$

$$S_1M\ 8 = S_1M\ 7b + (200 * Rutile_Mask)$$

$$S_1M\ 8a = LT(S_1M\ 8, 220) * GE(S_1M\ 8, 200)$$

$$S_1M\ 8b = S_1M\ 7b + (S_1M\ 8a * S_1M\ 8)$$

$$S_1M\ 9 = S_1M\ 8b + (220 * Quartz_Mask)$$

$$S_1M\ 9a = LT(S_1M\ 9, 230) * GE(S_1M\ 9, 220)$$

$$S_1M\ 9b = S_1M\ 8b + (S_1M\ 9a * S_1M\ 9)$$

$$S_1M\ 10 = S_1M\ 9b + (230 * Apatite_Mask)$$

$$S_1M\ 10a = LT(S_1M\ 10, 240) * GE(S_1M\ 10, 230)$$

$$S_1M\ 10b = S_1M\ 9b + (S_1M\ 10a * S_1M\ 10)$$

$$S_1M\ 11 = S_1M\ 10b + (240 * Kspar_Mask)$$

$$S_1M\ 11a = LT(S_1M\ 11, 250) * GE(S_1M\ 11, 240)$$

$$S_1M\ 11b = S_1M\ 10b + (S_1M\ 11a * S_1M\ 11)$$

$$S_1M\ 12 = S_1M\ 11b + (251 * Pt_Mask)$$

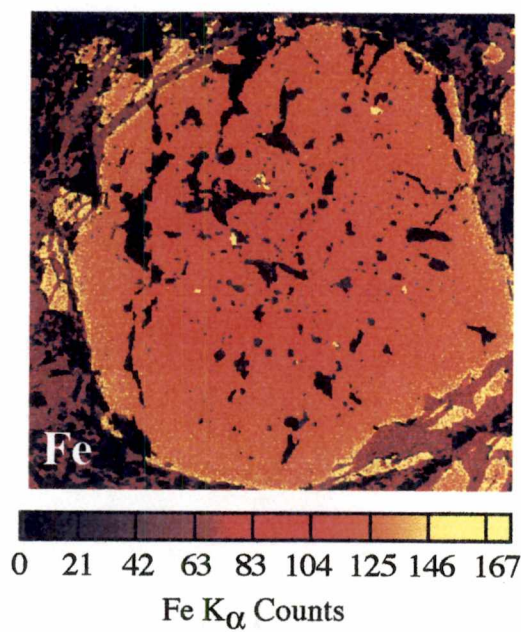
$$S_1M\ 12a = GE(S_1M\ 12, 251) \quad \text{This Leaves the points and holes.}$$

$$S_1M\ 12b = LT(S_1M\ 12, 251) \quad \text{This leaves holes for the points}$$

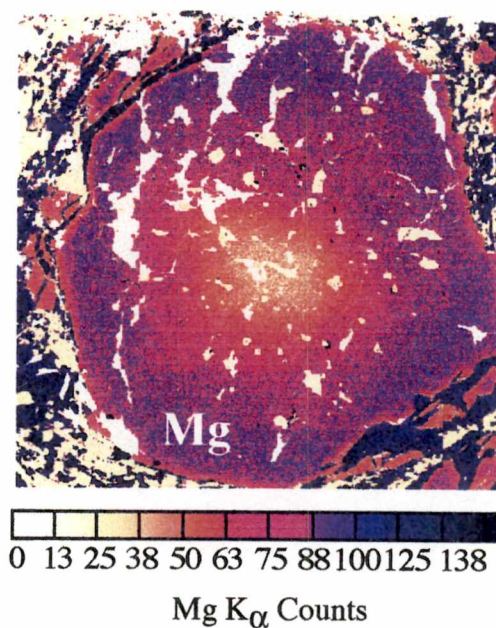
$$S_1M\ 12c = (S_1M\ 11b * S_1M\ 12b) + (S_1M\ 12a * 251) \text{ Remakes the Micrograph}$$

Appendix 2a: Qualitative X-ray Images of the Elements for Sample 2

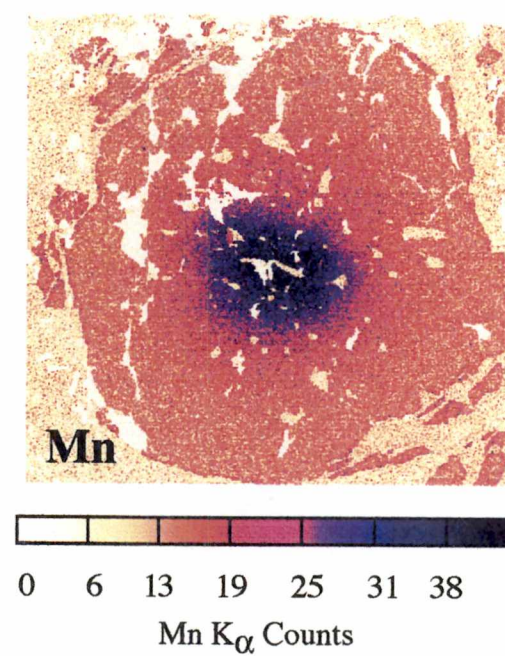
a.)



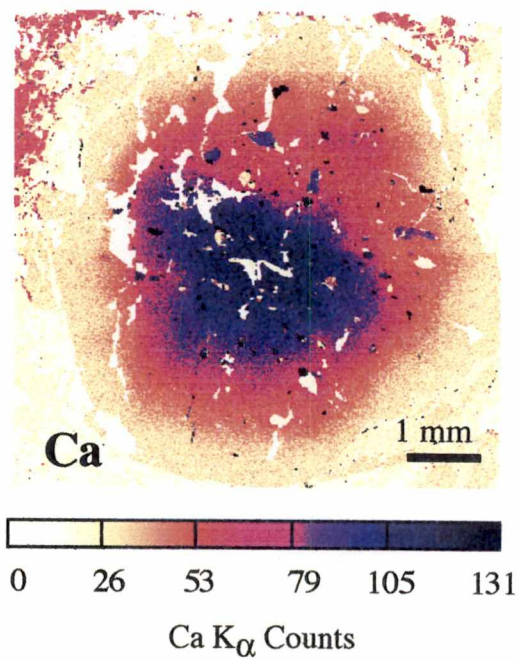
b.)



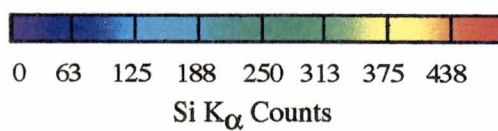
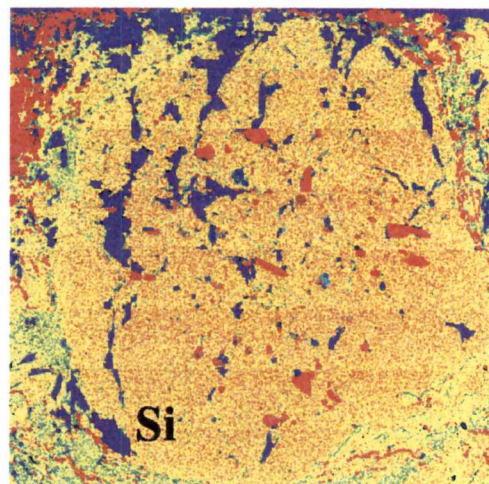
c.)



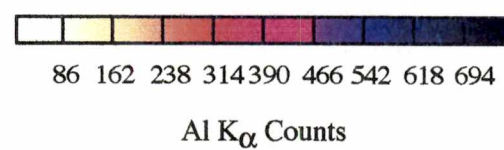
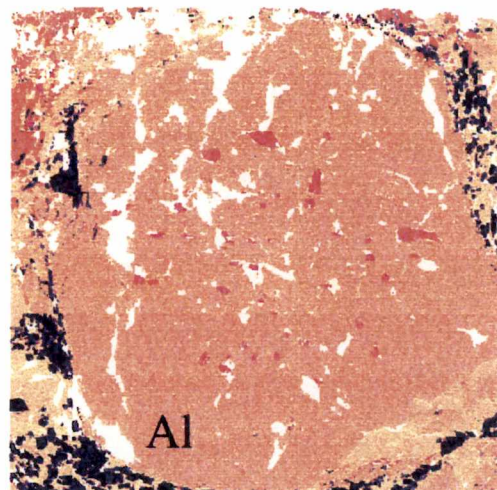
d.)



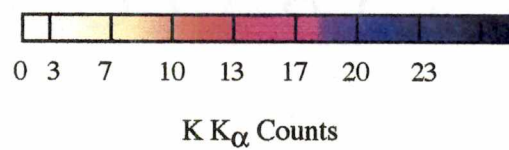
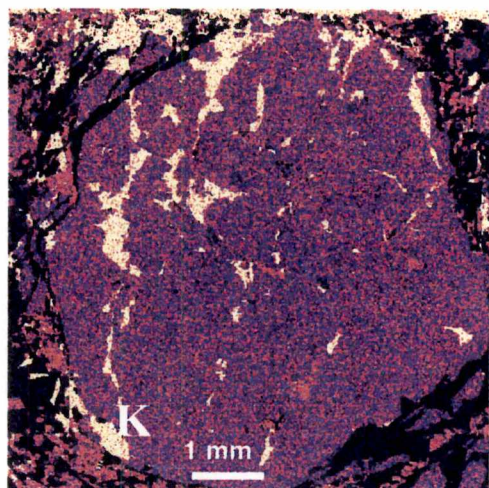
e.)



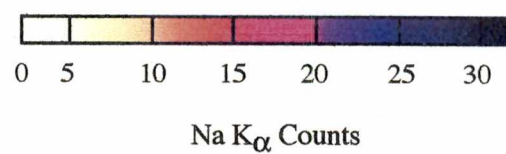
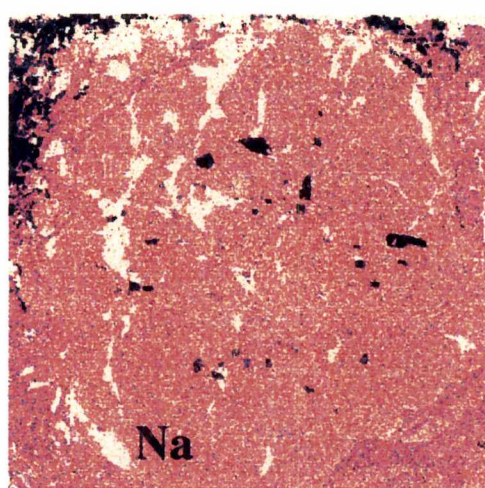
f.)



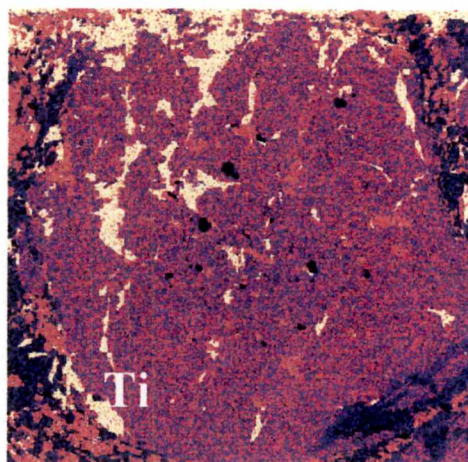
g.)



h.)



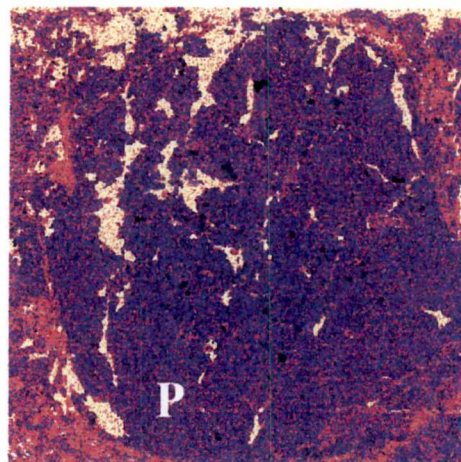
i.)



0 5 10 15 20 25 30

Ti K α Counts

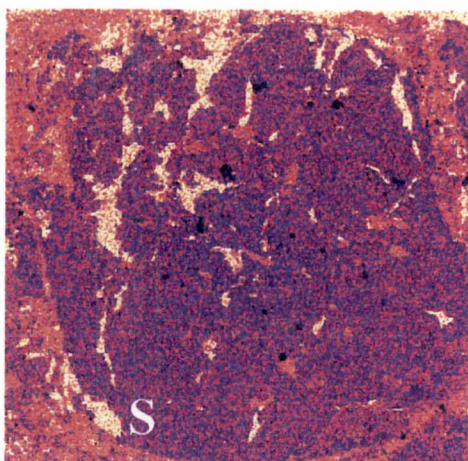
j.)



10 15 20 25 30 35 40 45 50

P K α Counts

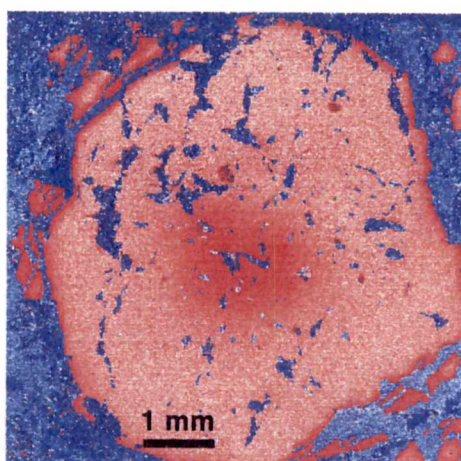
k.)



13 20 27 33 40 47 53 60

S K α Counts

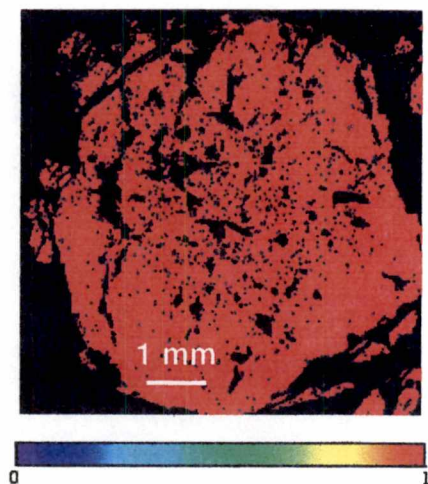
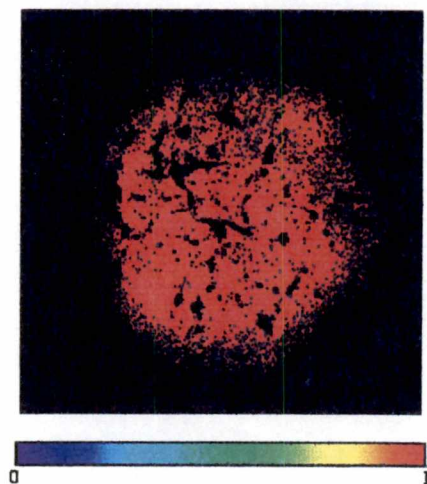
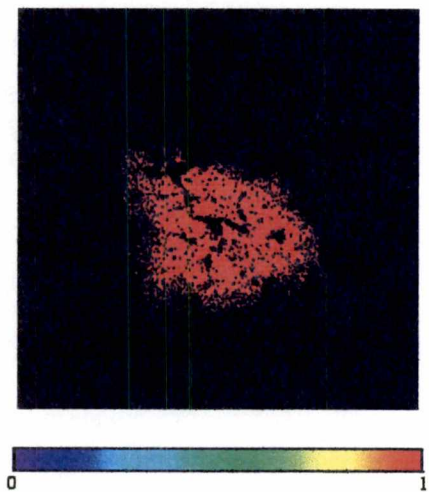
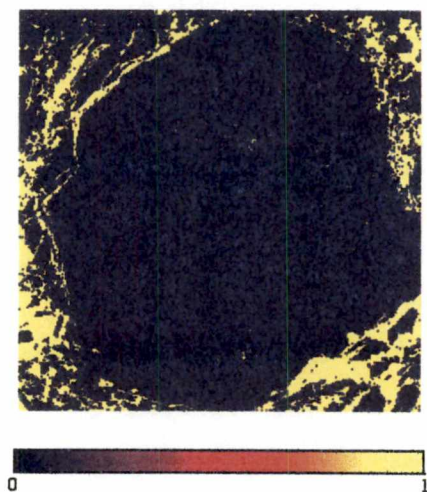
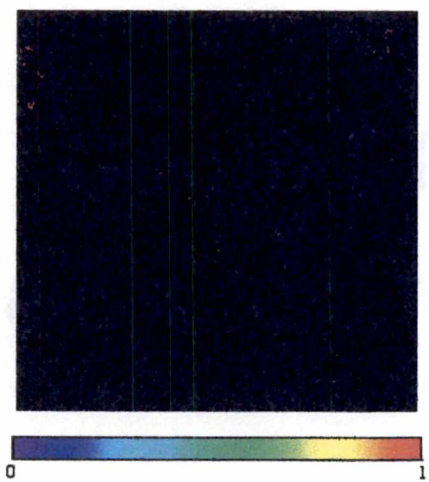
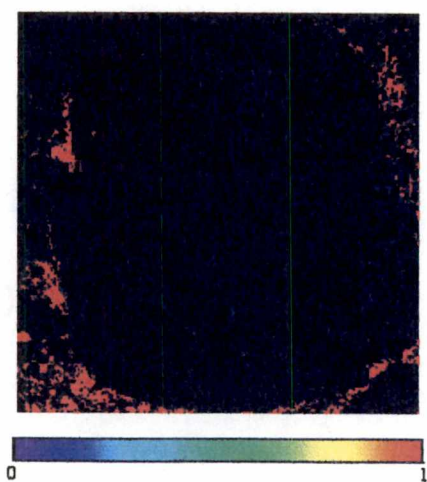
l.)

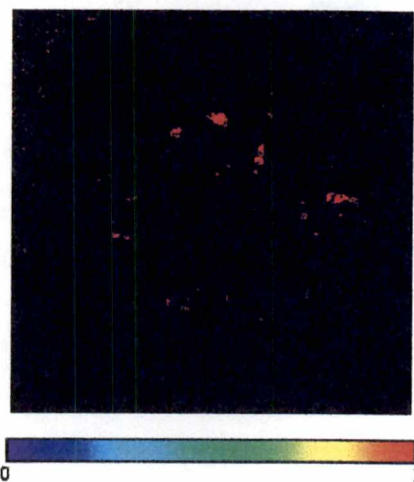
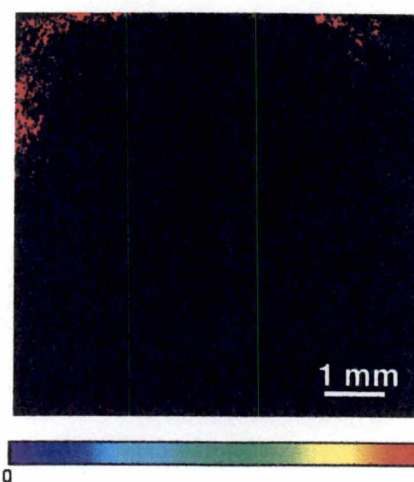
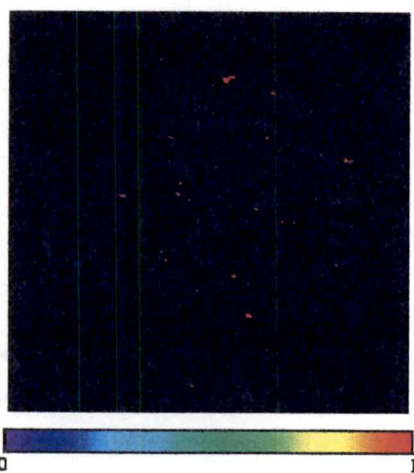
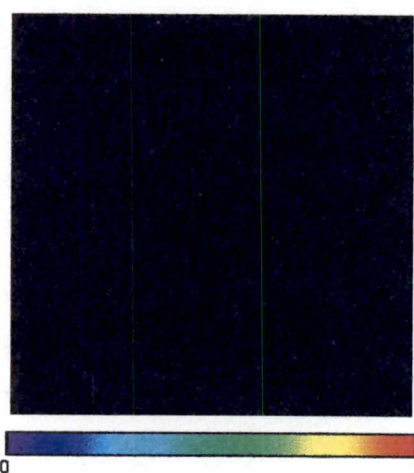
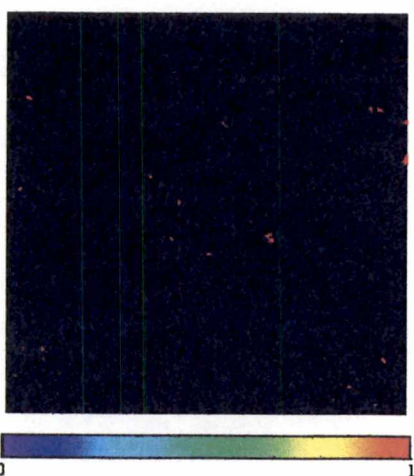
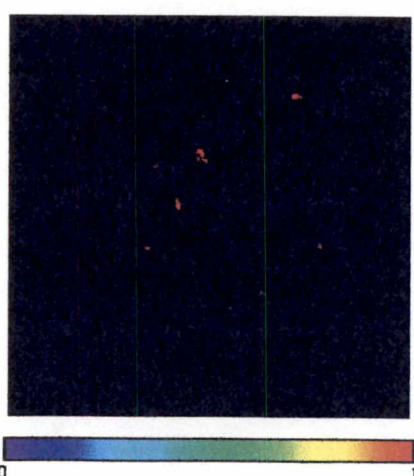


0.0 0.2 0.4 0.6 0.8 0.9

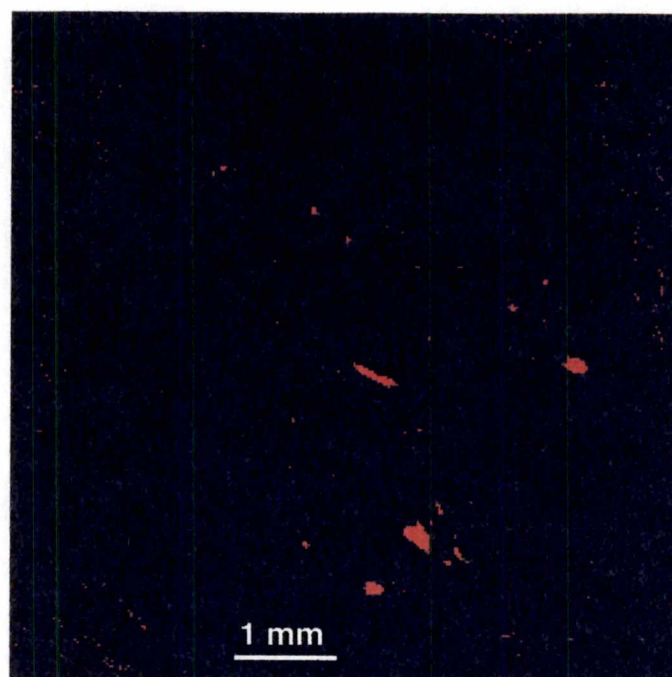
Fe/(Fe+Mg)

Appendix 2b: Qualitative Masks of the Minerals for Sample 2

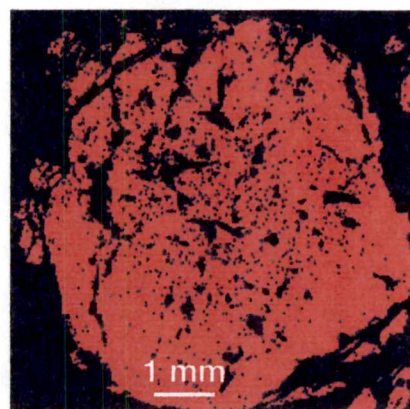
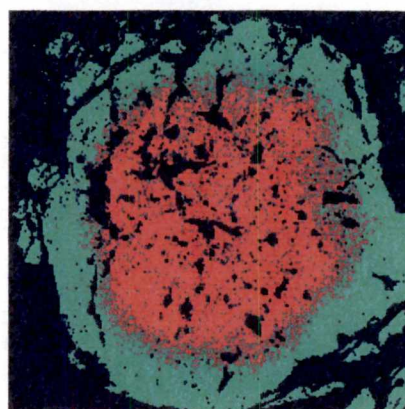
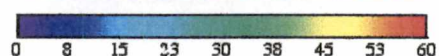
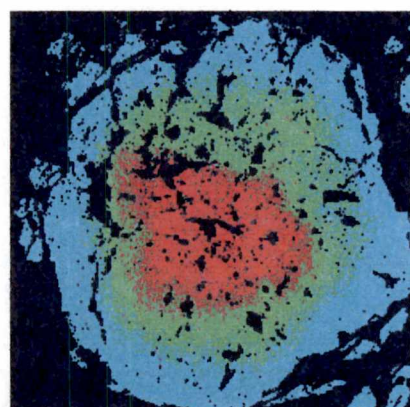
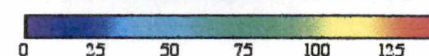
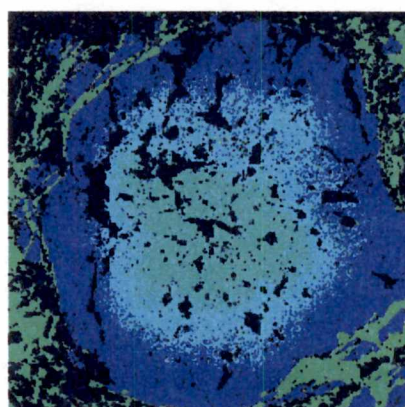
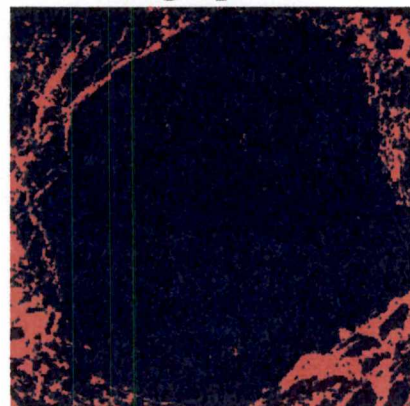
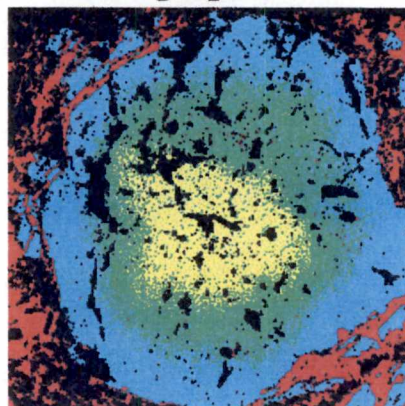
a.) Garnet Mask**b.) Garnet Medium Ca Mask****c.) Garnet High Ca Mask****d.) Biotite Mask****e.) Muscovite Mask****f.) Aluminum Silicate Mask**

g.) Plagioclase Ca Mask**h.) Plagioclase Na Mask****i.) Apatite Mask****j.) Monazite Mask****k.) Rutile Mask****l.) Ilmenite Mask**

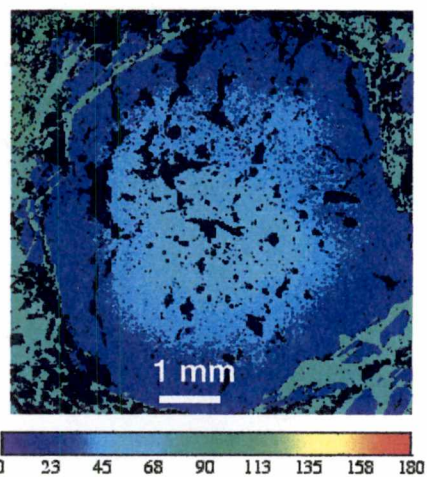
m.)

Quartz Mask

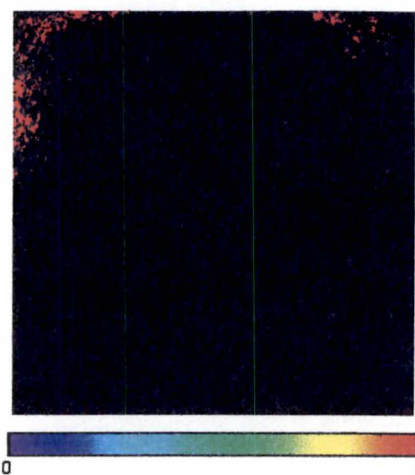
Appendix 2c: Micrographs for Sample 2

a.) Micrograph 1**b.) Micrograph 1a****c.) Micrograph 1b****d.) Micrograph 2****e.) Micrograph 2a****f.) Micrograph 2b**

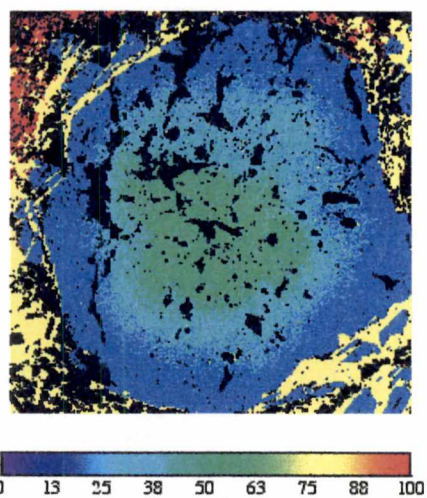
g.) Micrograph 3



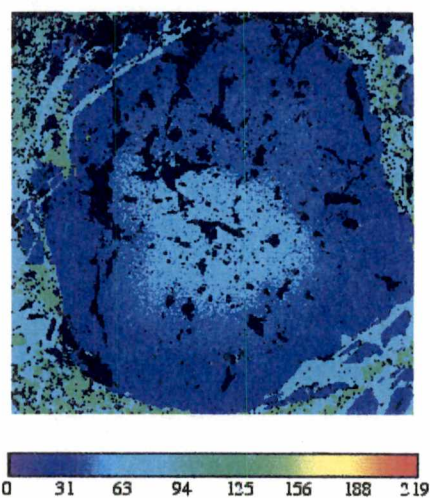
h.) Micrograph 3a



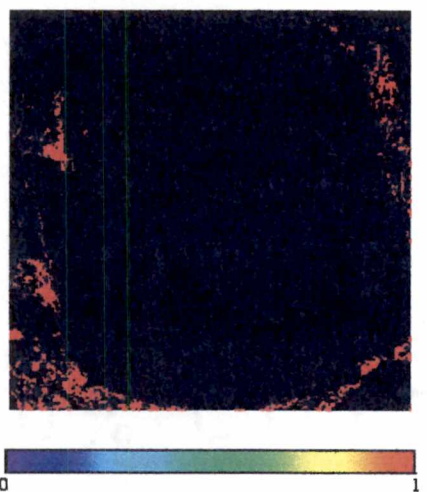
i.) Micrograph 3b



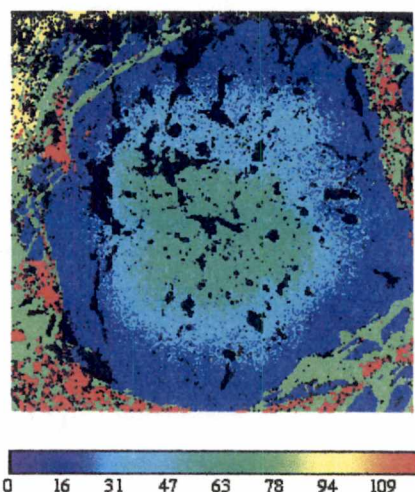
j.) Micrograph 4

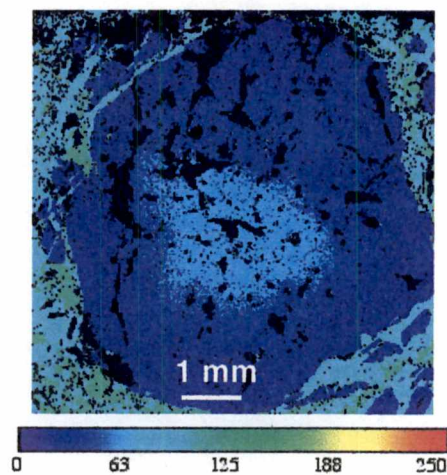
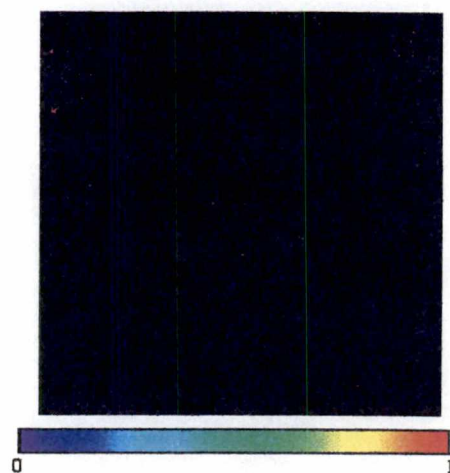
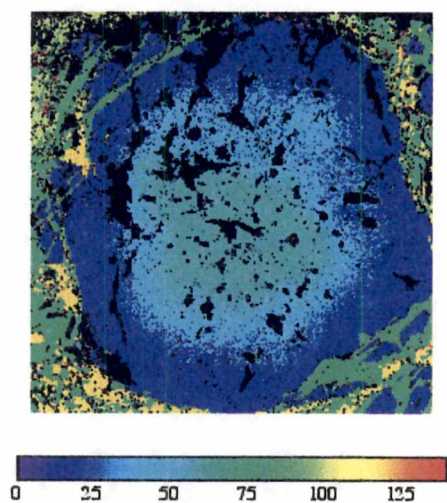
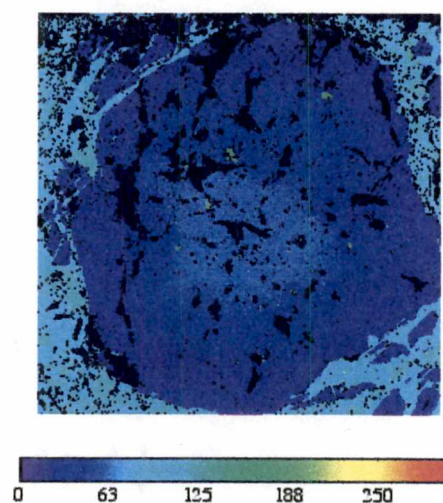
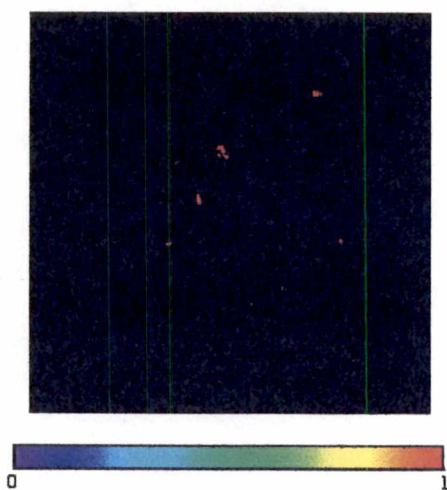
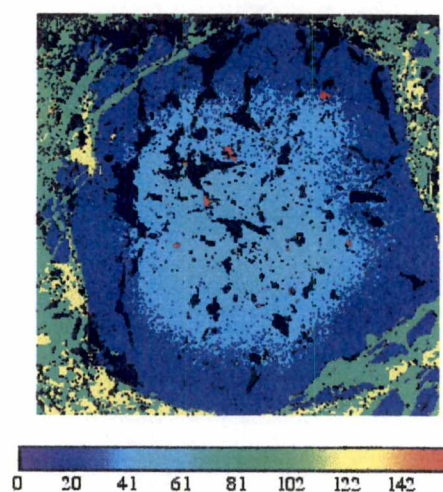


k.) Micrograph 4a

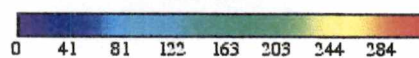
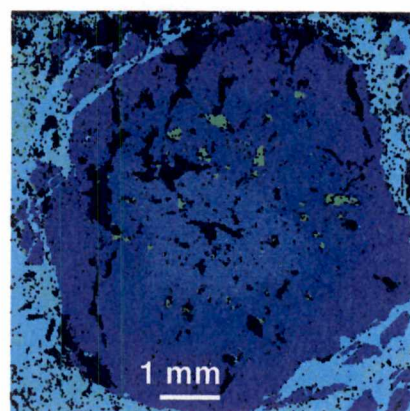


l.) Micrograph 4b

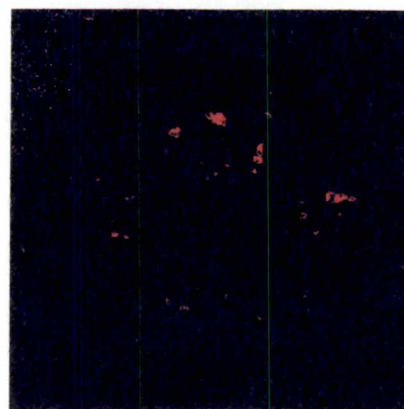


m.) Micrograph 5**n.) Micrograph 5a****o.) Micrograph 5b****p.) Micrograph 6****q.) Micrograph 6a****r.) Micrograph 6b**

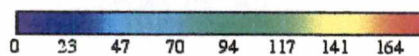
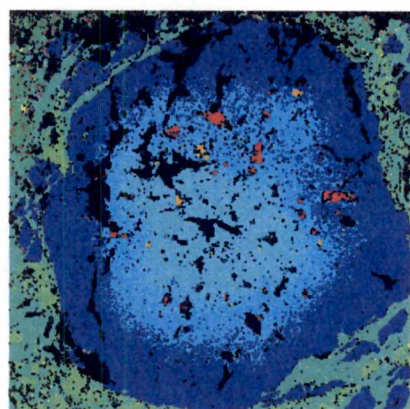
s.) Micrograph 7



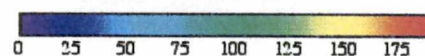
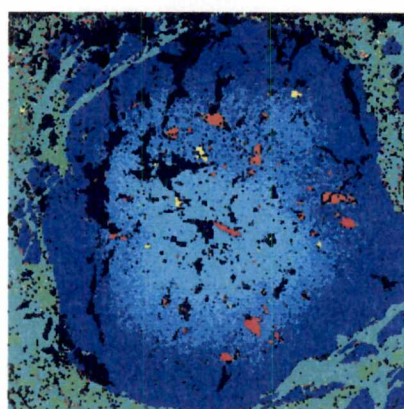
t.) Micrograph 7a



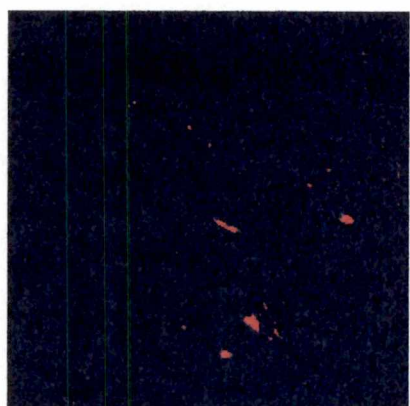
u.) Micrograph 7b



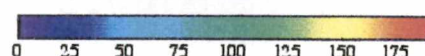
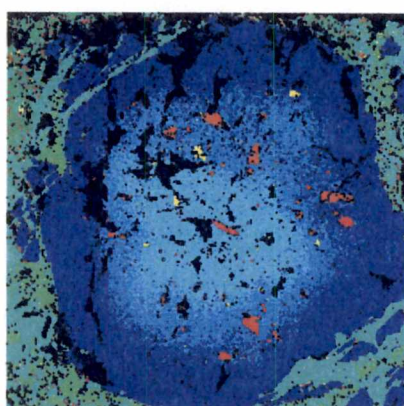
v.) Micrograph 8

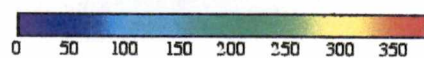
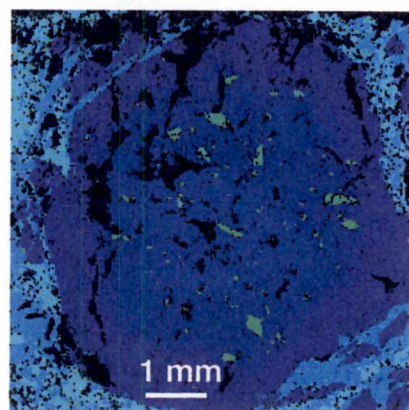
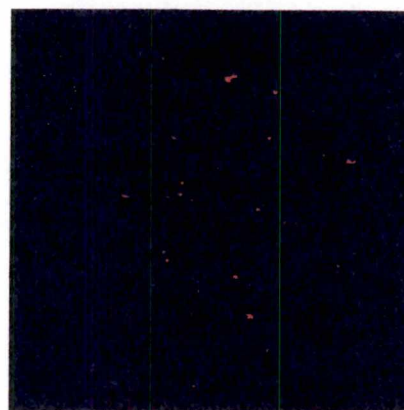
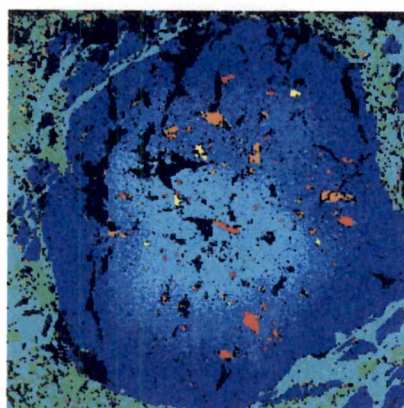
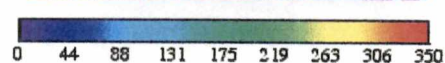
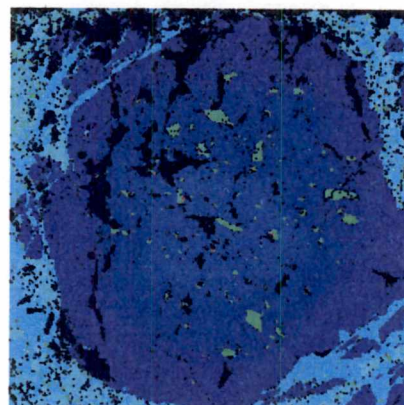
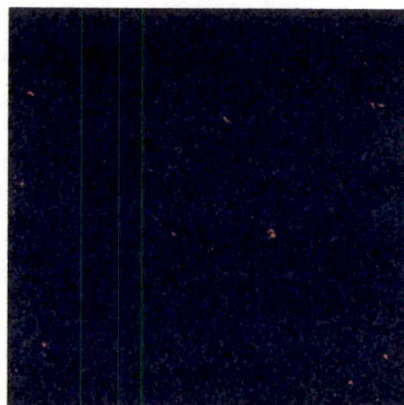
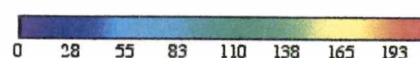
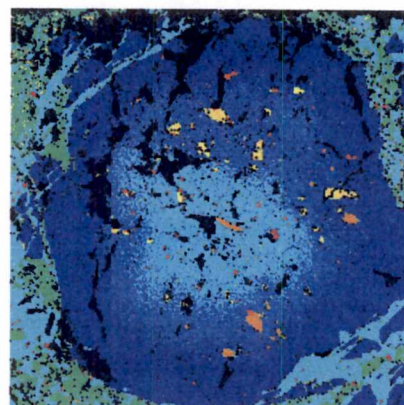


w.) Micrograph 8a

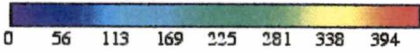
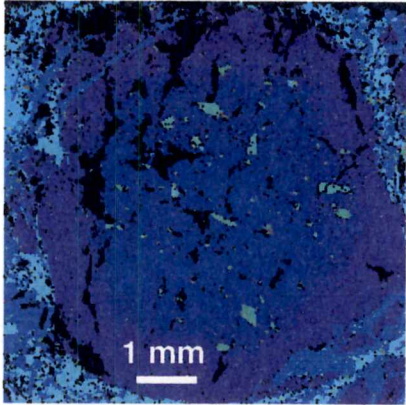


x.) Micrograph 8b

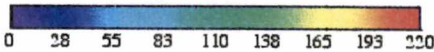
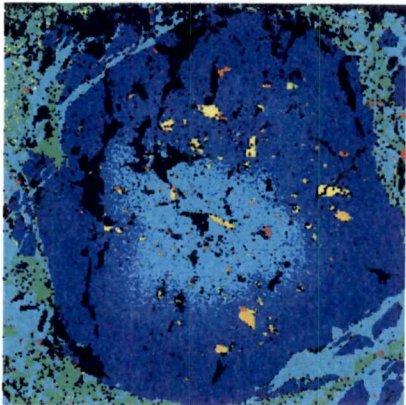


y.) Micrograph 9**z.) Micrograph 9a****aa.) Micrograph 9b****bb.) Micrograph 10****cc.) Micrograph 10a****dd.) Micrograph 10b**

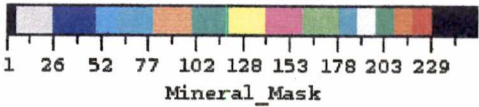
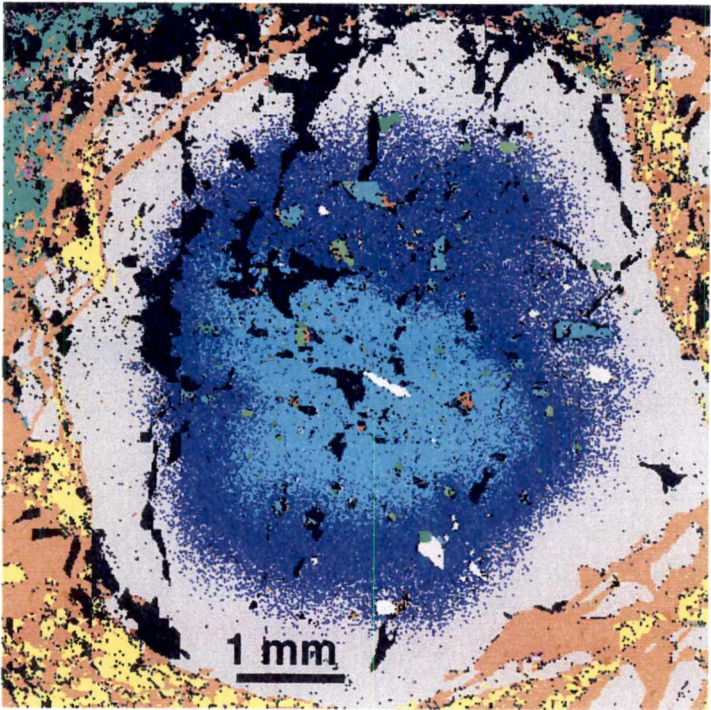
ee.) Micrograph 11



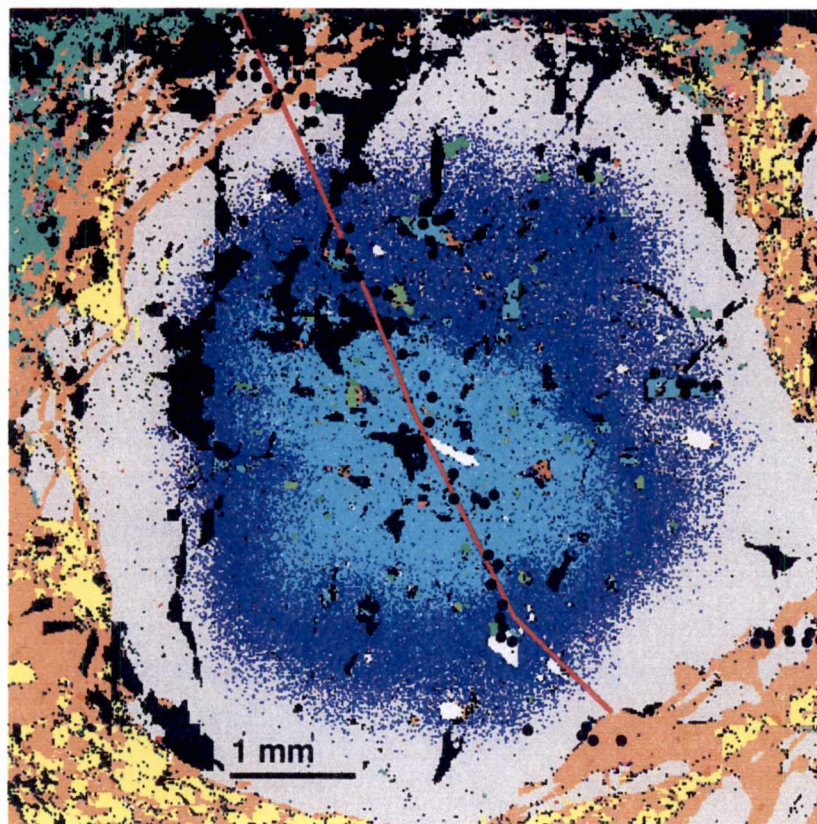
ff.) Micrograph 11b



gg.) Micrograph 11b3



hh.) Sample 2 Micrograph and Color Code



Explanation

	Traverse		Scale
	Garnet: Low Ca		Biotite
	Garnet Med Ca		Plagioclase: An 25
	Garnet Hi Ca		Plagioclase: An 45
	Al Silicate		Quartz
	Apatite		Ilmenite
	Rutile		QuantitativePoints

Appendix 2d: Micrograph Computer Code for Sample 2

Sample 2 Mineral Masks

The mineral masks for each Sample were pieced together in the computer program *Transform PPC 3.4*. To make the masks, the appropriate elemental maps were opened and combinations of intensity levels from different elements masked out the unwanted portions of the entire qualitative map. The only part of the qualitative map that was left to view was the desired mineral.

GE = $\geq$; GT = $>$; LE = $\leq$; LT = $<$; S₂ = Sample 2

Garnet_Fe_Mask = GE mask (S₂_Fe_Data, 90) * GT (S₂_Al_Data, 180).

Garnet_Med_Ca_Mask = GE (S₂_Al_Data, 190) * GE (S₂_Ca_Data, 50)
* LT (S₂_Na_Data, 20).

Garnet_High_Ca_Mask = GE (S₂_Al_Data, 200) * GE (S₂_Ca_Data, 85)
* LT (S₂_Na_Data, 22).

Biotite_Mask = GE (S₂_Al_Data, 80) * GT (S₂_Mg_Data, 60)
* GT (S₂_K_Data, 35).

Muscovite_Mask = GT (S₂_K_Data, 35) * LT (S₂_Mg_Data, 60)
* GE (S₂_Al_Data, 80).

Al_Silicate_Mask = GT (S₂_Al_Data, 570) * GT (S₂_Si_Data, 250).

Quartz_Mask = GT (S₂_Si_Data, 950) * LT (S₂_Al_Data, 50).

Apatite_Mask = GT (S₂_P_Data, 200) * GT (S₂_Ca_Data, 500).

Monazite_Mask = GT (S₂_P_Data, 50) * LE (S₂_Ca_Data, 60).

Rutile_Mask = GE (S₂_Ti_Data, 200) * LE (S₂_Fe_Data, 40).

Ilmenite_Mask = GT (S₂_Fe_Data, 100) * GT (S₂_Ti_Data, 100).

Plagioclase_Na_Mask = GE (S₂_Al_Data, 80) * GE (S₂_Na_Data, 90)
* LT (S₂_Ca_Data, 145).

Plagioclase_Ca_Mask = GE (S₂_Al_Data, 280) * GE (S₂_Ca_Data, 90)
* LE (S₂_Na_Data, 22).

$$K_Feldspar_Mask = GE (S_2_K_Data, 90) * LE (S_2_Na_Data, 40).$$

Micrograph Reconstruction Code

All Micrographs were pieced together in the program

Transform PPC 3.4. Since Transform only codes from 1 - 254 the counts had to be scaled to this range.

$S_2M\#$ = Sample 2 Micrograph number.

$$S_2M\ 1 = 20 * Gt_Mask + 40 * Garnet_Ca_Mask.$$

$$S_2M\ 1a = LE (S_2M\ 1, 60)$$

$$S_2M\ 1b = S_2M1 * S_2M1a$$

$$S_2M\ 2 = S_2M\ 1b + (80 * Bt_Mask)$$

$$S_2M\ 2a = LT (S_2M\ 2, 100) * GE (S_2M\ 2, 80)$$

$$S_2M\ 2b = S_2M\ 1b + (S_2M\ 2a * S_2M\ 2)$$

$$S_2M\ 3 = S_2M\ 2b + (100 * Na_Plag_Mask)$$

$$S_2M\ 3a = LT (S_2M\ 3, 120) * GE (S_2M\ 3, 100)$$

$$S_2M\ 3b = S_2M\ 2b + (S_2M\ 3a * S_2M\ 3)$$

$$S_2M\ 4 = S_2M\ 3b + (120 * Sill_Mask)$$

$$S_2M\ 4a = LT (S_2M\ 4, 140) * GE (S_2M\ 4, 120)$$

$$S_2M\ 4b = S_2M\ 3b + (S_2M\ 4a * S_2M\ 4)$$

$$S_2M\ 5 = S_2M\ 4b + (140 * Musc_Mask)$$

$$S_2M\ 5a = LT (S_2M\ 5, 160) * GE (S_2M\ 5, 140)$$

$$S_2M\ 5b = S_2M\ 4b + (S_2M\ 5a * S_2M\ 5)$$

$$S_2M\ 6 = S_2M\ 5b + (160 * Ilm_Mask)$$

$$S_2M\ 6a = LT (S_2M\ 6, 180) * GE (S_2M\ 6, 160)$$

$$S_2M\ 6b = S_2M\ 5b + (S_2M\ 6a * S_2M\ 6)$$

$$S_2M\ 7 = S_2M\ 6b + (180 * Ca_Plag_Mask)$$

$$S_2M\ 7a = LT (S_2M\ 7, 200) * GE (S_2M\ 7, 180)$$

$$S_2M\ 7b = S_2M\ 6b + (S_2M\ 7a * S_2M\ 7)$$

$$S_2M\ 8 = S_2M\ 7b + (200 * Rutile_Mask)$$

$$S_2M\ 8a = LT (S_2M\ 8, 220) * GE (S_2M\ 8, 200)$$

$$S_2M\ 8b = S_2M\ 7b + (S_2M\ 8a * S_2M\ 8)$$

$$\begin{aligned}
 S_2M\ 9 &= S_2M\ 8b + (220 * Quartz_Mask) \\
 S_2M\ 9a &= LT(S_2M\ 9, 230) * GE(S_2M\ 9, 220) \\
 S_2M\ 9b &= S_2M\ 8b + (S_2M\ 9a * S_2M\ 9)
 \end{aligned}$$

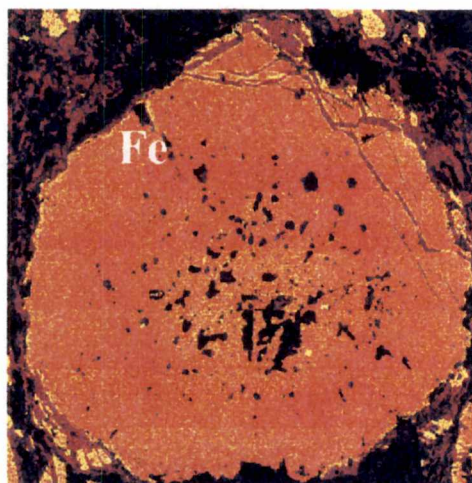
$$\begin{aligned}
 S_2M\ 10 &= S_2M\ 9b + (230 * Apatite_Mask) \\
 S_2M\ 10a &= LT(S_2M\ 10, 240) * GE(S_2M\ 10, 230) \\
 S_2M\ 10b &= S_2M\ 9b + (S_2M\ 10a * S_2M\ 10)
 \end{aligned}$$

$$\begin{aligned}
 S_2M\ 11 &= S_2M\ 10b + (240 * Kspar_Mask) \\
 S_2M\ 11a &= LT(S_2M\ 11, 250) * GE(S_2M\ 11, 240) \\
 S_2M\ 11b &= S_2M\ 10b + (S_2M\ 11a * S_2M\ 11)
 \end{aligned}$$

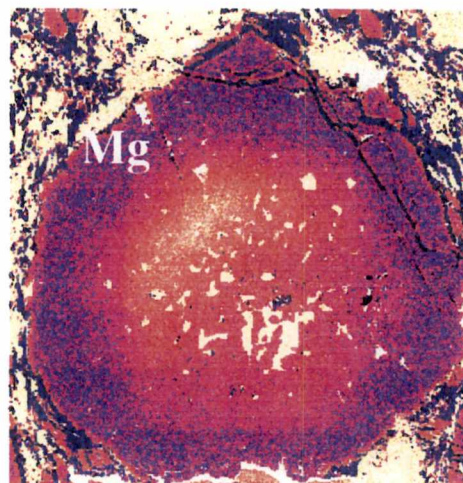
$$\begin{aligned}
 S_2M\ 12 &= S_2M\ 11b + (251 * Pt_Mask) \\
 S_2M\ 12a &= GE(S_2M\ 12, 251) && \text{This Leaves the points and holes.} \\
 S_2M\ 12b &= LT(S_2M\ 12, 251) && \text{This leaves holes for the points} \\
 S_2M\ 12c &= (S_2M\ 11b * S_2M\ 12b) + (S_2M\ 12a * 251) && \text{Remakes the Micrograph}
 \end{aligned}$$

Appendix 3a: Qualitative X-ray Images of the Elements for Sample 3

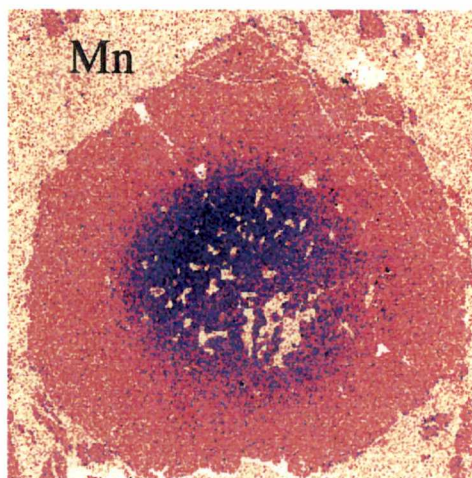
a.)

Fe K α Counts

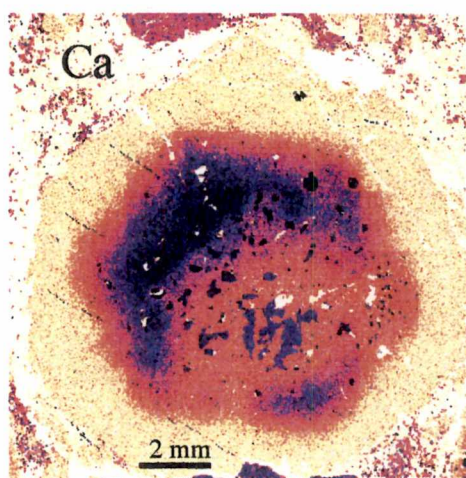
b.)

Mg K α Counts

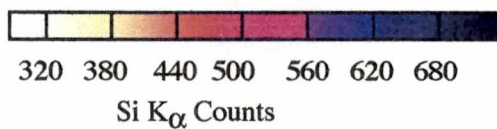
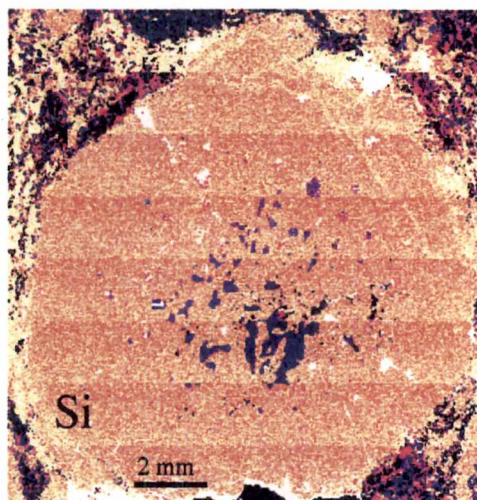
c.)

Mn K α Counts

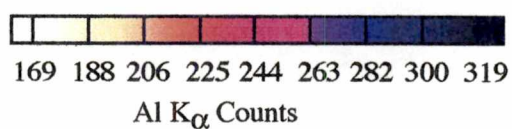
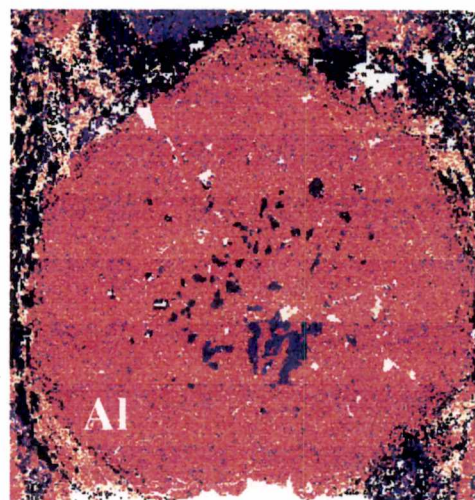
d.)

Ca K α Counts

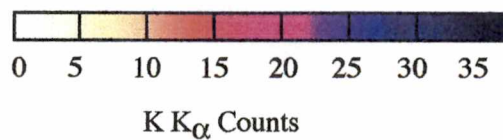
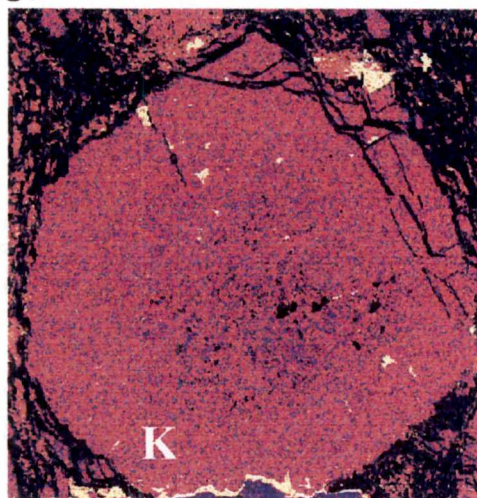
e.)



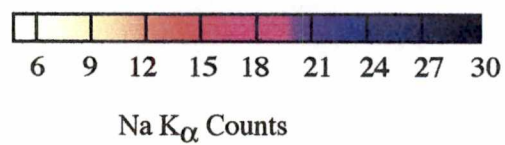
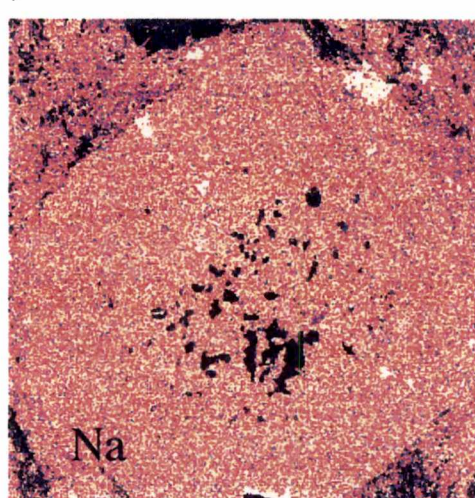
f.)



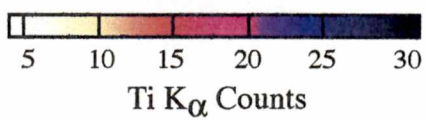
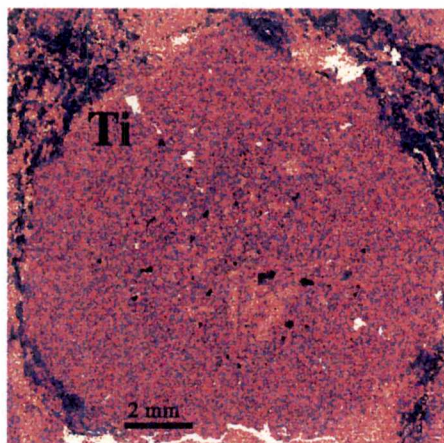
g.)



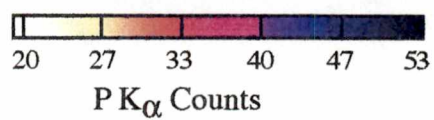
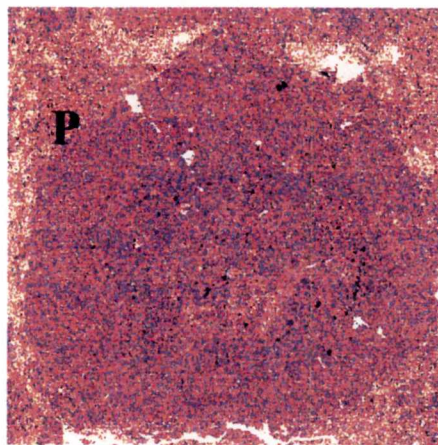
h.)



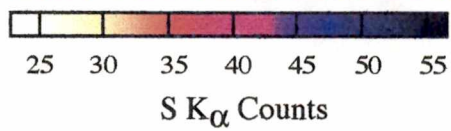
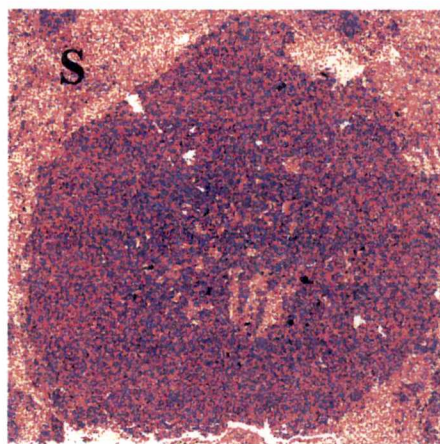
i.)



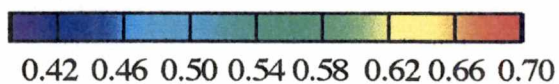
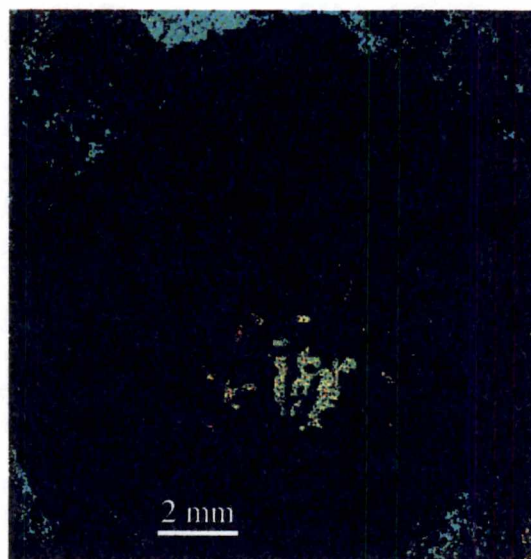
j.)



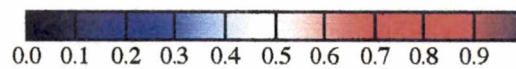
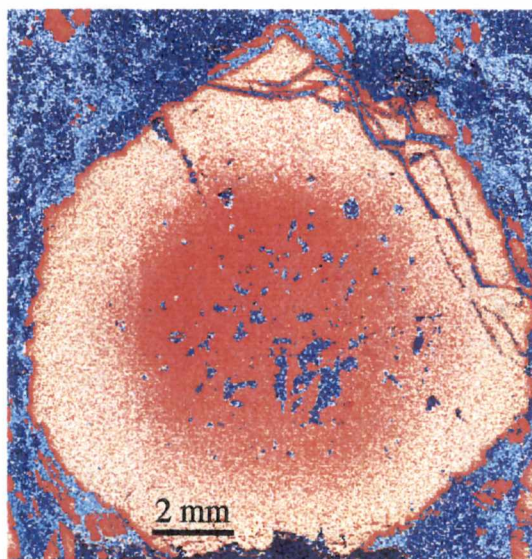
k.)



l.) Sample 3 Anorthite in plagioclase

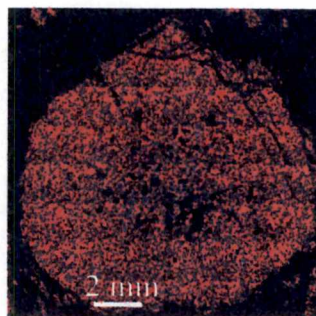
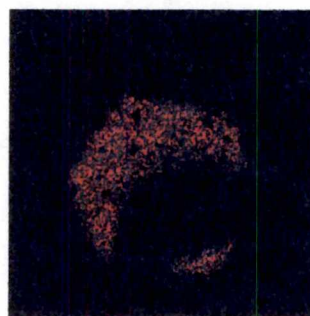
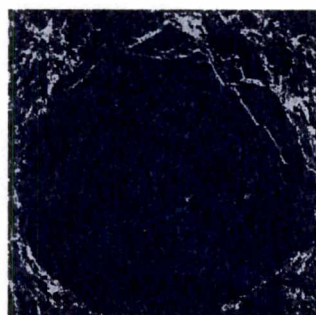
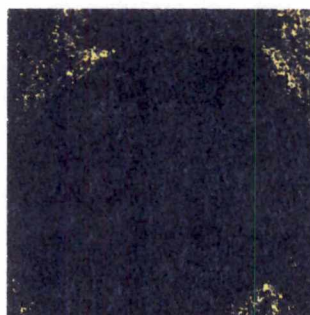
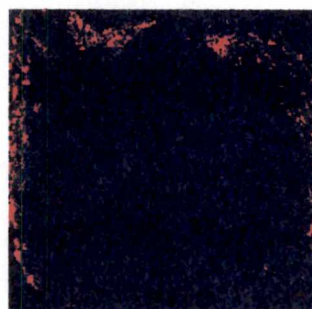
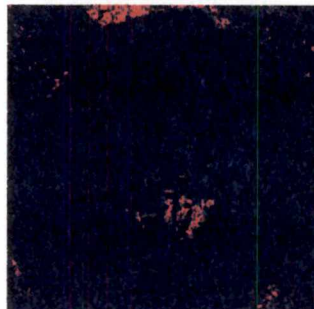


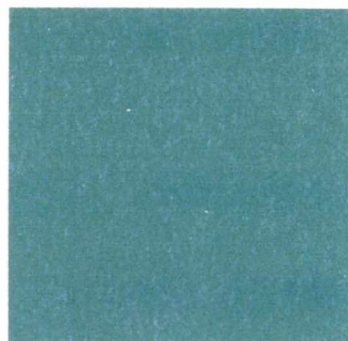
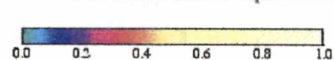
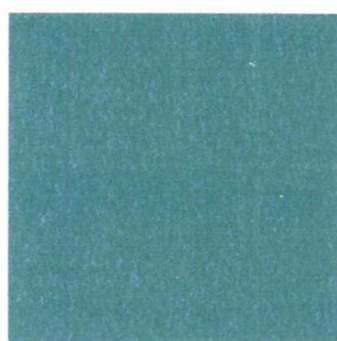
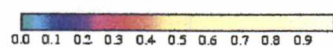
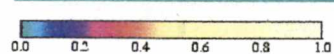
m.) Sample 3 Fe/Fe+Mg



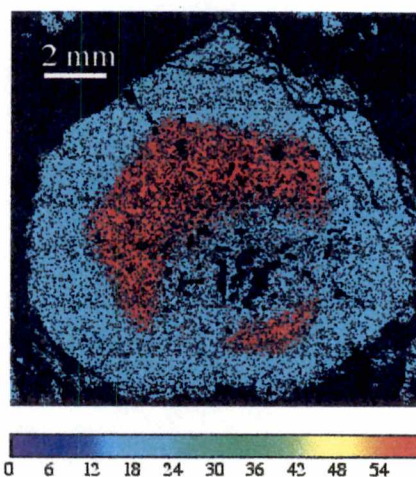
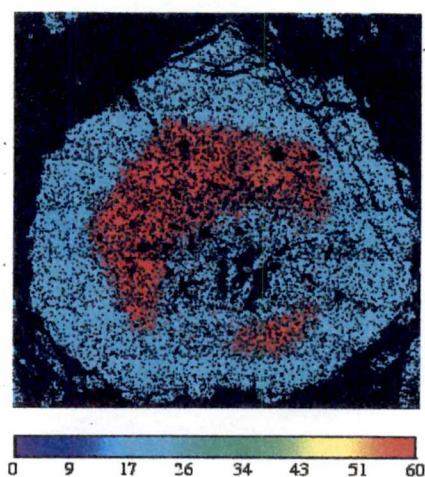
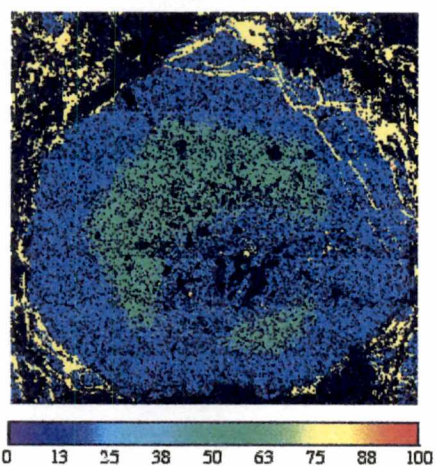
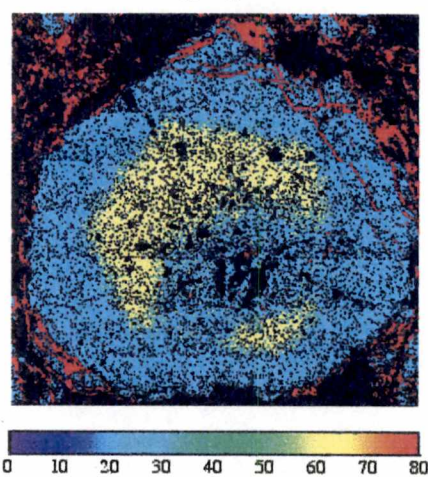
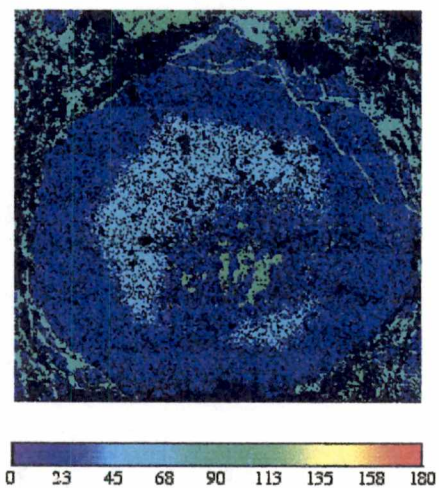
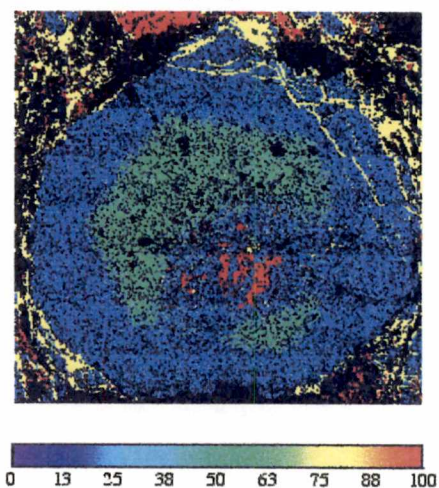
$\text{Fe}/(\text{Fe} + \text{Mg})$

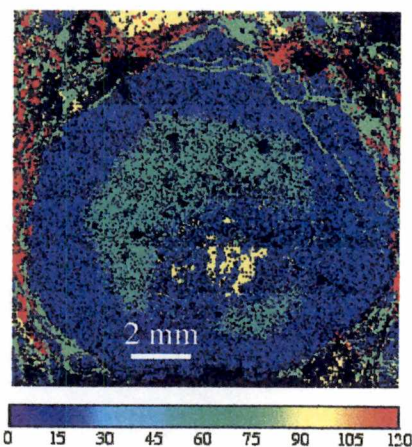
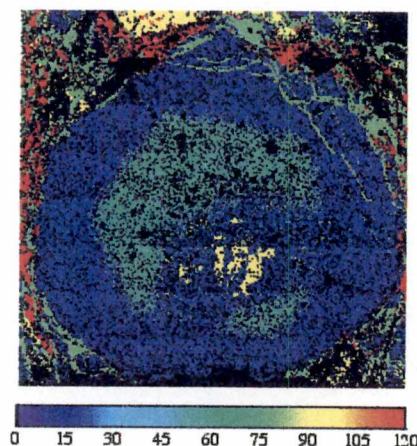
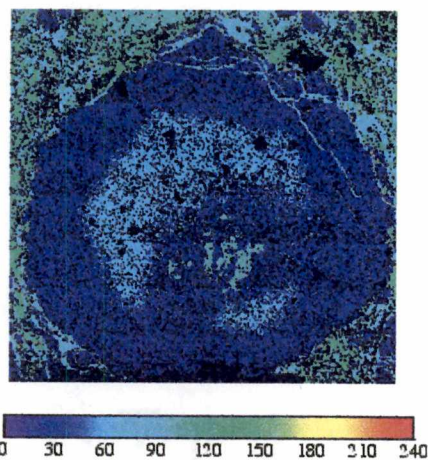
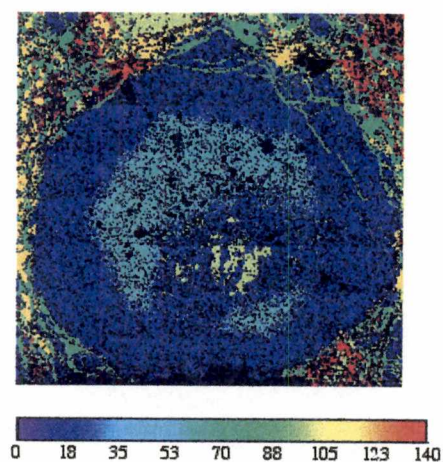
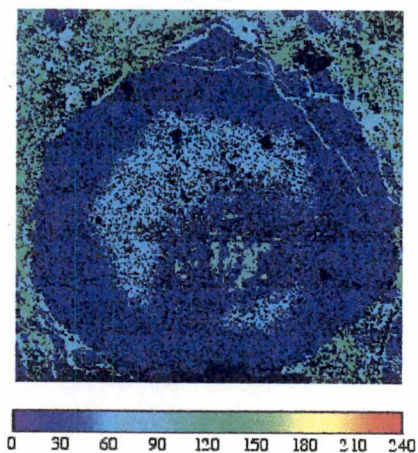
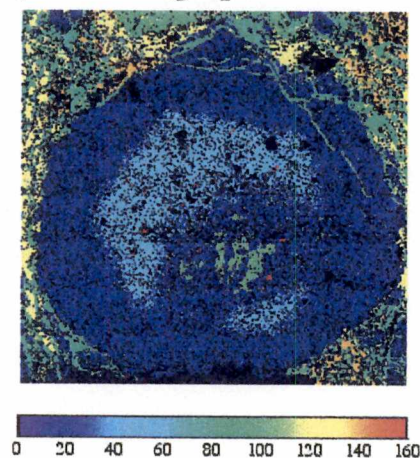
Appendix 3b: Qualitative Masks of the Minerals for Sample 3

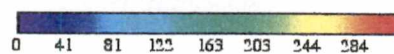
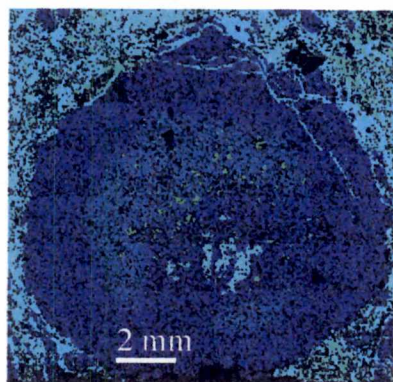
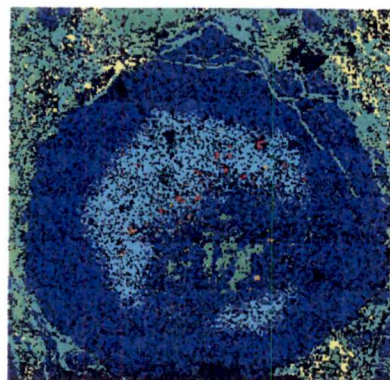
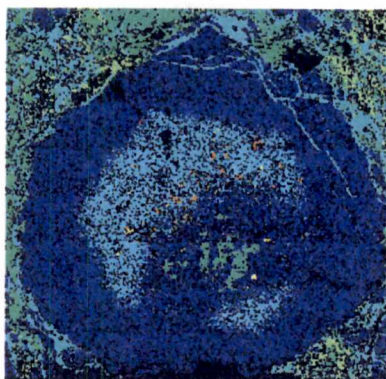
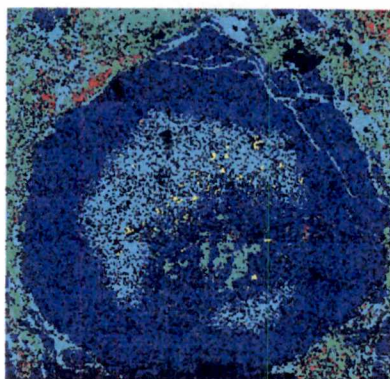
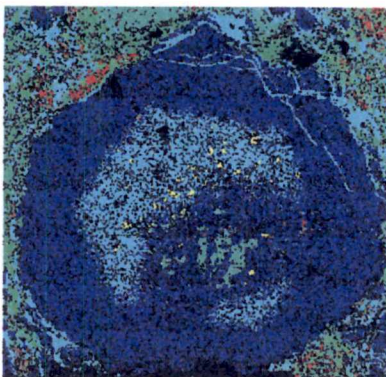
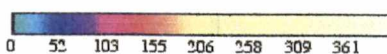
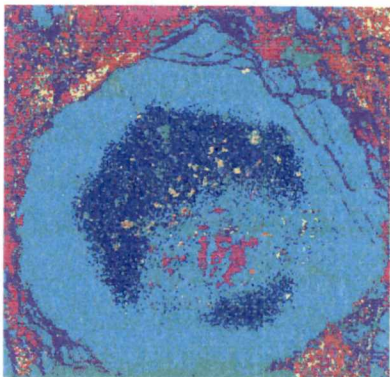
a.) Garnet Mask**b.) Garnet High Ca Zone****c.) Biotite Mask****d.) Muscovite Mask****e.) Al Silicate Mask****f.) Plagioclase Na Mask**

g.) Quartz Mask**h.) Ilmenite Mask****i.) Rutile Mask****j.) Monazite Mask****k.) Apatite Mask****l.) Plagioclase An Mask**

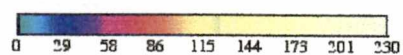
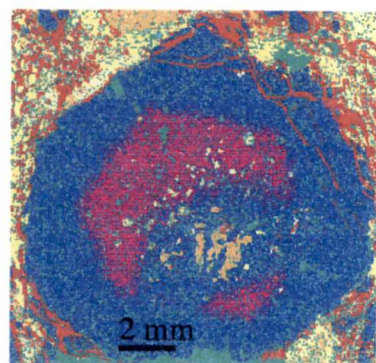
Appendix 3c: Micrographs for Sample 3

a.) Micrograph 1**b.) Micrograph 1b****c.) Micrograph 2****d.) Micrograph 2b****e.) Micrograph 3****f.) Micrograph 3b**

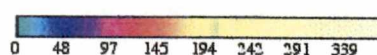
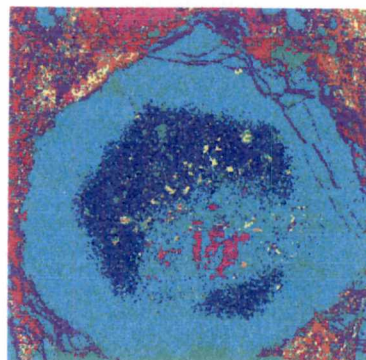
g.) Micrograph 4**h.) Micrograph 4b****i.) Micrograph 5****j.) Micrograph 5b****k.) Micrograph 6****l.) Micrograph 6b**

m.) Micrograph 7**n.) Micrograph 7b****o.) Micrograph 8b****p.) Micrograph 9****q.) Micrograph 9b****r.) Micrograph 10**

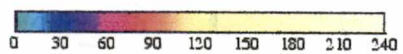
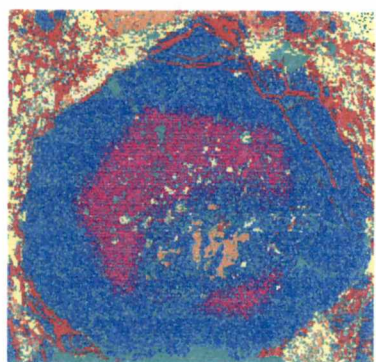
s.) Micrograph 10b



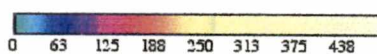
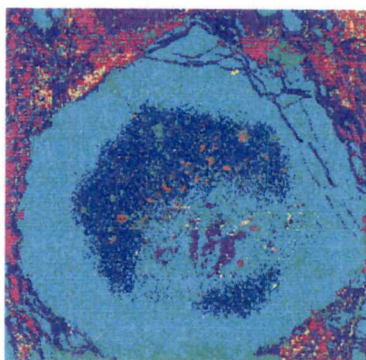
t.) Micrograph 11



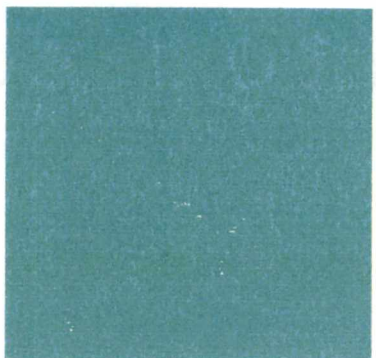
u.) Micrograph 11b



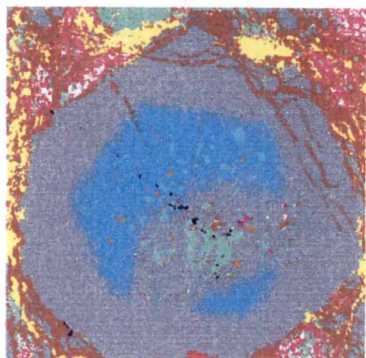
v.) Micrograph 12

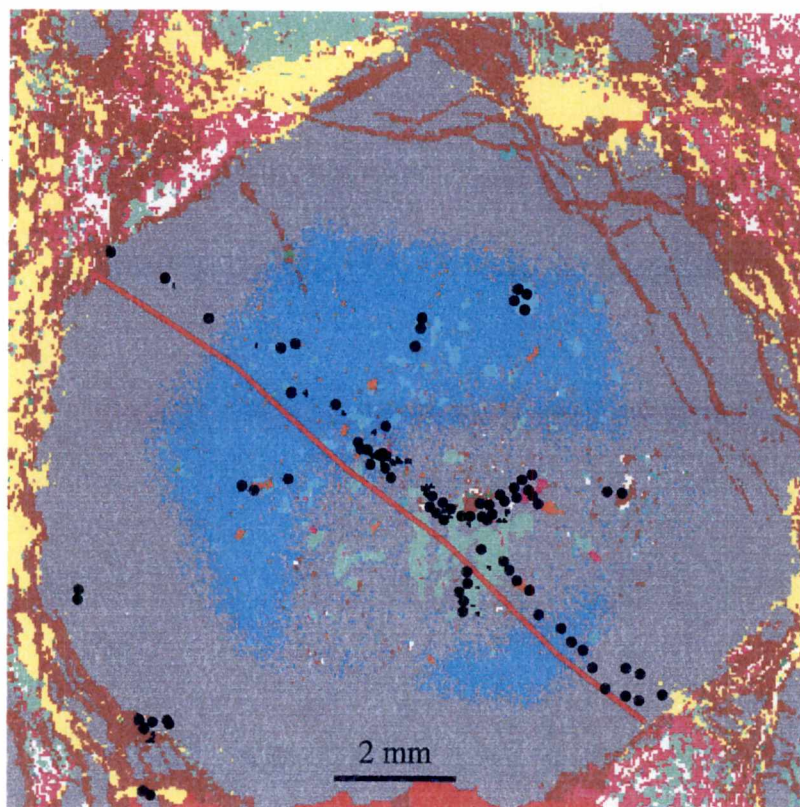


w.) Micrograph 12a



x.) Micrograph 12c



y.) **Sample 3 Micrograph and Color Code****Explanation**

— Traverse
— Scale

	Garnet: Low Ca	Plagioclase: Low An	
	Garnet: Mid-High Ca	Plagioclase: High An	
	Biotite	Aluminum Silicate	
	Muscovite	Ilmenite	
	Quartz	Apatite	
	Rutile	K-Feldspar	
	Quantitative Points	Hole	

Appendix 3d: Micrograph Computer Code for Sample 3

Sample 3 Mineral Masks

The mineral masks for each Sample were pieced together in the computer program *Transform PPC 3.4*. To make the masks, the appropriate elemental maps were opened and combinations of intensity levels from different elements masked out the unwanted portions of the entire qualitative map. The only part of the qualitative map that was left to view was the desired mineral.

GE = $\geq$; GT = $>$; LE = $\leq$; LT = $<$; S₃ = Sample 3

Garnet_Fe_Mask = GE mask (S₃_Fe_Data, 90) * GT (S₃_Al_Data, 180).

Garnet_High_Ca_Mask = GE (S₃_Al_Data, 220) * GE (S₃_Ca_Data, 60)
* LT (S₃_Na_Data, 20).

Biotite_Mask = GE (S₃_Al_Data, 160) * GT (S₃_Mg_Data, 80)
* GT (S₃_K_Data, 40).

Muscovite_Mask = GT (S₃_K_Data, 40) * LT (S₃_Mg_Data, 40)
* GE (S₃_Al_Data, 130).

Al_Silicate_Mask = GT (S₃_Al_Data, 600) * GT (S₃_Si_Data, 200).

Quartz_Mask = GT (S₃_Si_Data, 1000).

Apatite_Mask = GT (S₃_P_Data, 100) * GT (S₃_Ca_Data, 50).

Monazite_Mask = GT (S₃_P_Data, 100) * LE (S₃_Ca_Data, 50).

Rutile_Mask = GE (S₃_Ti_Data, 200) * LE (S₃_Fe_Data, 40).

Ilmenite_Mask = GT (S₃_Fe_Data, 120) * GT (S₃_Ti_Data, 40).

Plagioclase_Na_Mask = GE (S₃_Al_Data, 240) * GE (S₃_Na_Data, 40)
* LT (Ca_Data, 100).

Plagioclase_Ca_Mask = GE (S₃_Al_Data, 280) * GE (S₃_Ca_Data, 100)
* LE (S₃_Na_Data, 45).

K_Feldspar_Mask = GE (S₃_K_Data, 185) * LE (S₃_Na_Data, 30).

Pt_Mask = A matrix 512 X 512 with 1 representing the quantitative points.

Micrograph Reconstruction Code

All Micrographs were pieced together in the program

Transform PPC 3.4. Since Transform only codes from 1 - 254 the counts had to be scaled to this range.

S₃M # = Sample 3 Micrograph Number.

S₃M 1 = 20 * Gt_Mask + 40 * Garnet_Ca_Mask.

S₃M 1a = LE (S₃M 1, 60)

S₃M 1b = S₃M1 * S₃M1a

S₃M 2 = S₃M 1b + (80 * Bt_Mask)

S₃M 2a = LT (S₃M 2, 100) * GE (S₃M 2, 80)

S₃M 2b = S₃M 1b + (S₃M 2a * S₃M 2)

S₃M 3 = M 2b + (100 * Na_Pl原因_Mask)

S₃M 3a = LT (S₃M 3, 120) * GE (S₃M 3, 100)

S₃M 3b = S₃M 2b + (S₃M 3a * S₃M 3)

S₃M 4 = S₃M 3b + (120 * Sill_Mask)

S₃M 4a = LT (S₃M 4, 140) * GE (S₃M 4, 120)

S₃M 4b = S₃M 3b + (S₃M 4a * S₃M 4)

S₃M 5 = S₃M 4b + (140 * Musc_Mask)

S₃M 5a = LT (S₃M 5, 160) * GE (S₃M 5, 140)

S₃M 5b = S₃M 4b + (S₃M 5a * S₃M 5)

S₃M 6 = S₃M 5b + (160 * Ilm_Mask)

S₃M 6a = LT (S₃M 6, 180) * GE (S₃M 6, 160)

S₃M 6b = S₃M 5b + (S₃M 6a * S₃M 6)

S₃M 7 = S₃M 6b + (180 * Ca_Pl原因_Mask)

S₃M 7a = LT (S₃M 7, 200) * GE (S₃M 7, 180)

S₃M 7b = S₃M 6b + (S₃M 7a * S₃M 7)

S₃M 8 = S₃M 7b + (200 * Rutile_Mask)

S₃M 8a = LT (S₃M 8, 220) * GE (S₃M 8, 200)

S₃M 8b = S₃M 7b + (S₃M 8a * S₃M 8)

$$\begin{aligned}
 S_3M\ 9 &= S_3M\ 8b + (220 * Quartz_Mask) \\
 S_3M\ 9a &= LT(S_3M\ 9, 230) * GE(S_3M\ 9, 220) \\
 S_3M\ 9b &= S_3M\ 8b + (S_3M\ 9a * S_3M\ 9)
 \end{aligned}$$

$$\begin{aligned}
 S_3M\ 10 &= S_3M\ 9b + (230 * Apatite_Mask) \\
 S_3M\ 10a &= LT(S_3M\ 10, 240) * GE(S_3M\ 10, 230) \\
 S_3M\ 10b &= S_3M\ 9b + (S_3M\ 10a * S_3M\ 10)
 \end{aligned}$$

$$\begin{aligned}
 S_3M\ 11 &= S_3M\ 10b + (240 * Kspar_Mask) \\
 S_3M\ 11a &= LT(S_3M\ 11, 250) * GE(S_3M\ 11, 240) \\
 S_3M\ 11b &= S_3M\ 10b + (S_3M\ 11a * S_3M\ 11)
 \end{aligned}$$

$$\begin{aligned}
 S_3M\ 12 &= S_3M\ 11b + (251 * Pt_Mask) \\
 S_3M\ 12a &= GE(S_3M\ 12, 251) && \text{This Leaves the points and holes.} \\
 S_3M\ 12b &= LT(S_3M\ 12, 251) && \text{This leaves holes for the points} \\
 S_3M\ 12c &= (S_3M\ 11b * S_3M\ 12b) + (S_3M\ 12a * 251) && \text{Remakes the Micrograph}
 \end{aligned}$$

Appendix 4a: Sample 1 Garnet Electron Microprobe Analyses

Appendix 4a; Sample 1 Garnet

Oxides	Sample		Region		Point#		1		4		6		7		8		9		10		11		12		20	
	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄
SiO ₂	36.3	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8	36.8
TiO ₂	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Al ₂ O ₃	21.1	21.4	21.4	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2	21.2
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	4.62	5.37	5.37	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84	4.84
CaO	1.17	1.15	1.15	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.12
MnO	1.50	1.28	1.28	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43	1.43
FeO	33.7	33.4	33.4	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2	34.2
Na ₂ O	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	98.4	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5	99.5

Cations Based on 12 Oxygens

Si	2.94	2.94	2.94	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95	2.95
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.02	2.02	2.02	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.56	0.64	0.64	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58	0.58
Ca	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Mn	0.10	0.09	0.09	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Fe	2.27	2.22	2.22	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4a; Sample 1 Garnet

Oxides	Sample											
	Region	1	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁
Point#		42	**@43	**@46	**@49	50	51	52	55	**@54	**@60	**@63
SiO ₂		37.6	38.1	37.5	37.8	38.3	37.7	37.9	36.8	40.3	37.2	
TiO ₂		0.04	0.00	0.04	0.03	0.03	0.06	0.03	0.02	0.01	0.04	
Al ₂ O ₃		21.5	21.9	21.7	21.7	21.8	21.6	22.0	21.2	22.0	21.6	
Cr ₂ O ₃		0.04	0.00	0.04	0.05	0.02	0.00	0.02	0.03	0.00	0.00	
MgO		6.76	6.91	6.44	6.51	6.72	5.89	7.80	4.36	3.23	5.92	
CaO		4.26	4.34	4.89	5.00	5.23	5.22	4.43	3.11	2.99	3.13	
MnO		1.96	1.97	1.95	1.92	1.85	1.82	0.92	1.31	1.50	0.99	
FeO		27.0	26.3	26.4	26.0	25.7	26.9	26.3	32.5	28.8	30.3	
Na ₂ O		0.01	0.02	0.00	0.00	0.00	0.02	0.02	0.02	1.08	0.01	
Total		99.1	99.6	99.0	98.9	99.6	99.1	99.3	99.3	99.8	99.1	

Cations Based on 12 Oxygens

Si	2.96	2.97	2.95	2.97	2.98	2.97	2.97	2.95	2.95	3.14	2.95
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.99	2.02	2.01	2.01	2.00	2.00	2.00	2.01	2.01	2.02	2.02
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.79	0.80	0.76	0.76	0.78	0.69	0.69	0.91	0.52	0.38	0.70
Ca	0.36	0.36	0.41	0.42	0.44	0.44	0.44	0.37	0.27	0.25	0.27
Mn	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.06	0.09	0.10	0.07
Fe	1.76	1.71	1.73	1.70	1.67	1.77	1.77	1.70	2.17	1.88	2.00
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16	0.00
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.93	8.00

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4a; Sample 1 Garnet

Oxides	Sample Region	Point#	1							
			R ₄ *@87	R ₄ *@87	R ₄ *@87	R ₄ *@87	R ₄ *@87	R ₄ *@87	R ₃ **@94	R ₄
			88	89	90	92	95	96		
SiO ₂			36.1	36.2	37.1	38.5	38.2	36.5		
TiO ₂			0.03	0.03	0.02	0.02	0.05	0.03		
Al ₂ O ₃			20.6	21.1	21.3	22.2	21.9	21.1		
Cr ₂ O ₃			0.00	0.00	0.01	0.00	0.02	0.00		
MgO			4.06	4.45	5.00	8.43	8.52	4.66		
CaO			1.49	1.27	1.11	3.45	3.60	1.17		
MnO			1.47	1.40	1.44	0.76	0.89	1.41		
FeO			34.5	33.7	33.9	26.8	26.7	34.4		
Na ₂ O			0.03	0.03	0.02	0.01	0.01	0.03		
Total			98.2	98.2	99.9	100.1	99.8	99.3		

Cations Based on 12 Oxygens

Si	2.95	2.95	2.96	2.96	2.95	2.94
Ti	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.98	2.02	2.00	2.02	1.99	2.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.49	0.54	0.59	0.97	0.98	0.56
Ca	0.13	0.11	0.10	0.28	0.30	0.10
Mn	0.10	0.10	0.10	0.05	0.06	0.10
Fe	2.34	2.28	2.25	1.72	1.71	2.30
Na	0.01	0.01	0.00	0.00	0.00	0.00
Total	8.00	8.00	8.00	8.00	8.00	8.00

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim;
R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b: Sample 2 Garnet Electron Microprobe Analyses

Appendix 4b; Sample 2 Garnet

Oxides	Sample		2		2		2		2		2		2		2		2	
	Region	R4	*@3	R4	*@4	R4	*@8	R4	*@9	R4	R4	R4	R4	R4	R4	R4	R3	R2
Point#	1	2	2	2	5	6	7	10	11	12	13	14						
SiO ₂	37.3	37.3	37.4	37.3	37.4	37.3	37.0	37.4	38.3	38.5	38.4	38.4						
TiO ₂	0.02	0.01	0.02	0.02	0.02	0.02	0.05	0.03	0.04	0.02	0.03	0.03						
Al ₂ O ₃	21.5	21.4	21.6	21.5	21.6	21.5	21.2	21.4	22.0	22.0	22.0	22.0						
Cr ₂ O ₃	0.00	0.03	0.03	0.00	0.03	0.00	0.00	0.01	0.02	0.03	0.00	0.00						
MgO	4.93	4.95	5.07	6.61	5.07	6.61	4.74	5.46	10.02	9.84	9.77	9.77						
CaO	1.17	1.04	1.01	1.03	1.01	1.03	1.09	1.09	1.42	1.36	1.71	1.71						
MnO	1.33	1.36	1.26	0.82	1.26	0.82	1.40	1.25	0.60	0.65	0.67	0.67						
FeO	33.3	33.6	33.7	31.8	33.7	31.8	33.5	33.2	26.4	26.6	26.7	25.3						
Na ₂ O	0.01	0.02	0.03	0.02	0.03	0.02	0.00	0.03	0.01	0.02	0.01	0.02						
Total	99.4	99.7	100.1	99.1	99.1	99.1	99.0	99.8	98.9	99.1	99.2	99.6						

Cations Based on 12 Oxygens

Si	2.98	2.98	2.97	2.96	2.97	2.96	2.98	2.97	2.97	2.98	2.97	2.97						
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01						
Al	2.02	2.01	2.02	2.01	2.02	2.01	2.01	2.00	2.01	2.01	2.00	1.99						
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
Mg	0.59	0.59	0.60	0.78	0.60	0.78	0.57	0.65	1.16	1.13	1.13	0.98						
Ca	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.12	0.11	0.14	0.37						
Mn	0.09	0.09	0.09	0.06	0.09	0.06	0.10	0.08	0.04	0.04	0.04	0.06						
Fe	2.22	2.24	2.24	2.10	2.24	2.10	2.25	2.20	1.71	1.72	1.72	1.63						
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00						

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Sample	2	2	2	2	2	2	2	2	2	2	2	2	2
Region	R ₃	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂
Point#	15	16	17	18	19	24	25	26	27	28	31	32	32
Oxides													
SiO ₂	38.4	38.5	38.3	38.4	38.4	38.7	38.7	38.7	38.8	38.3	38.3	38.3	38.3
TiO ₂	0.03	0.05	0.04	0.01	0.03	0.03	0.01	0.05	0.03	0.02	0.02	0.02	0.02
Al ₂ O ₃	21.9	21.9	22.0	21.9	21.8	21.9	21.8	21.8	21.9	22.0	22.0	22.0	22.0
Cr ₂ O ₃	0.01	0.00	0.00	0.01	0.03	0.00	0.00	0.01	0.00	0.06	0.06	0.06	0.06
MgO	8.88	8.46	8.46	8.40	8.31	8.17	8.35	8.38	8.34	8.49	8.49	8.49	8.49
CaO	3.46	4.23	4.18	4.30	4.36	4.49	4.08	3.92	3.95	3.98	3.98	3.98	3.98
MnO	0.76	1.18	1.17	1.28	1.32	1.37	1.32	1.32	1.37	1.20	1.20	1.20	1.20
FeO	25.8	24.6	24.7	25.0	25.2	24.5	24.9	24.6	25.0	24.8	24.8	24.8	24.8
Na ₂ O	0.01	0.01	0.00	0.00	0.01	0.02	0.00	0.01	0.01	0.00	0.00	0.00	0.00
Total	99.2	98.9	98.9	99.3	99.5	99.2	99.2	98.8	99.3	98.9	98.9	98.9	98.9

Cations Based on 12 Oxygens

Si	2.97	2.99	2.98	2.98	2.98	3.00	3.00	3.01	3.00	2.98	2.98	2.98	2.98
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.00	2.00	2.01	2.00	1.99	2.00	1.99	2.00	2.00	2.02	2.02	2.02	2.02
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.03	0.98	0.98	0.97	0.96	0.94	0.97	0.97	0.96	0.98	0.98	0.98	0.98
Ca	0.29	0.35	0.35	0.36	0.36	0.37	0.34	0.33	0.33	0.33	0.33	0.33	0.33
Mn	0.05	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08
Fe	1.67	1.60	1.61	1.62	1.62	1.59	1.62	1.60	1.62	1.61	1.61	1.61	1.61
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.99	8.00	8.00	8.00	8.00	8.00

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Oxides	Sample Region	2		2		2		2		2		2		2		2	
		R ₂	R ₁	R ₁	redo #34	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁
	**@31																
Point#	33	34	35	36	37	38	39	40	41	42							
SiO ₂	38.6	38.2	38.5	38.4	38.1	37.8	37.6	37.4	37.2	37.3							
TiO ₂	0.04	0.06	0.04	0.09	0.12	0.08	0.09	0.09	0.10	0.07							
Al ₂ O ₃	21.9	21.9	21.9	21.6	21.4	21.4	21.2	21.1	21.0	20.9							
Cr ₂ O ₃	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.04	0.02	0.02							
MgO	8.52	8.07	8.20	6.84	5.49	4.66	3.71	3.11	3.06	2.87							
CaO	3.93	4.61	4.66	6.89	8.65	9.19	9.22	9.37	9.21	9.07							
MnO	1.21	1.52	1.63	2.09	2.94	3.62	4.57	5.10	5.32	5.23							
FeO	24.9	24.4	24.8	23.2	22.5	22.6	22.5	22.8	23.2	23.4							
Na ₂ O	0.00	0.01	0.02	0.02	0.00	0.01	0.00	0.00	0.01	0.00							
Total	99.0	98.7	99.7	99.1	99.3	99.3	99.0	99.0	99.1	98.8							

Cations Based on 12 Oxygens

Si	2.99	2.98	2.97	2.99	2.98	2.97	2.99	2.98	2.97	2.99							
Ti	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00							
Al	2.00	2.01	1.99	1.98	1.98	1.98	1.99	1.98	1.97	1.97							
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
Mg	0.99	0.94	0.94	0.80	0.64	0.55	0.44	0.37	0.36	0.34							
Ca	0.33	0.39	0.39	0.58	0.73	0.77	0.78	0.80	0.79	0.78							
Mn	0.08	0.10	0.11	0.14	0.20	0.24	0.31	0.34	0.36	0.36							
Fe	1.61	1.59	1.60	1.51	1.47	1.48	1.49	1.51	1.54	1.56							
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00							

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Sample Region	Point#	2		2		2		2		2		2		2	
		R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₃
Oxides	43	45	46	47	48	49	50	51	52	53					
SiO ₂	37.3	37.1	37.0	37.3	37.3	37.3	37.6	37.9	38.5	36.9					
TiO ₂	0.06	0.12	0.09	0.15	0.12	0.09	0.12	0.07	0.10	2.22					
Al ₂ O ₃	21.0	20.9	20.8	21.0	21.2	21.1	21.4	21.5	21.8	20.9					
Cr ₂ O ₃	0.00	0.07	0.03	0.00	0.00	0.01	0.01	0.02	0.02	0.00					
MgO	2.89	2.76	3.26	3.32	3.13	3.69	3.66	5.99	7.74	7.27					
CaO	9.05	9.37	9.25	9.32	9.29	8.99	9.01	7.82	5.43	5.70					
MnO	5.22	5.38	5.11	4.86	5.12	4.53	4.56	2.47	1.36	1.44					
FeO	23.4	23.3	22.8	22.8	22.9	23.0	22.7	23.1	24.3	24.7					
Na ₂ O	0.00	0.02	0.02	0.02	0.00	0.00	0.00	0.03	0.01	0.00					
Total	98.9	99.0	98.3	98.8	99.0	98.6	99.0	98.9	99.1	99.2					

Cations Based on 12 Oxygens

Si	2.99	2.97	2.97	2.98	2.97	2.97	2.98	2.97	2.99	2.90					
Ti	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.13					
Al	1.98	1.97	1.97	1.97	1.99	1.98	2.00	1.99	1.99	1.93					
Cr	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Mg	0.35	0.33	0.39	0.40	0.37	0.44	0.43	0.70	0.90	0.85					
Ca	0.78	0.80	0.80	0.80	0.79	0.77	0.77	0.66	0.45	0.48					
Mn	0.35	0.37	0.35	0.33	0.35	0.31	0.31	0.16	0.09	0.10					
Fe	1.56	1.55	1.52	1.52	1.52	1.13	1.51	1.51	1.57	1.62					
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00					

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Sample Region	2		2		2		2		2		2		2		2		2	
	R ₃	R ₃	R ₃	R ₃	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	
Oxides	Point#	54	55	56	59	60	61	62	63	64	65	**@72						
SiO ₂		38.1	38.3	38.3	38.4	37.4	36.9	36.6	36.2	35.2	19.3							
TiO ₂		0.06	0.07	0.02	0.04	0.02	0.04	0.01	0.05	0.05	0.16							
Al ₂ O ₃		21.7	21.5	21.9	22.0	21.4	21.3	21.2	20.8	20.2	11.2							
Cr ₂ O ₃		0.01	0.01	0.03	0.02	0.00	0.00	0.05	0.00	0.06	0.00							
MgO		7.39	7.09	7.99	8.90	6.83	6.58	6.10	5.09	4.01	1.93							
CaO		5.94	6.76	5.10	2.78	1.34	1.32	1.31	1.31	1.28	0.98							
MnO		1.55	1.63	1.29	0.79	0.73	0.73	0.90	1.12	1.46	1.44							
FeO		23.7	23.6	25.0	26.5	31.2	31.7	33.0	33.6	34.5	32.5							
Na ₂ O		0.01	0.01	0.02	0.02	0.00	0.02	0.01	0.02	0.01	0.11							
Total		98.5	99.0	99.6	99.5	98.9	98.6	99.1	98.2	96.8	67.6							

Cations Based on 12 Oxygens

Si	2.98	2.98	2.98	2.96	2.97	2.97	2.94	2.92	2.94	2.92	2.42								
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02								
Al	2.00	1.98	1.98	2.00	2.01	2.00	2.00	1.99	1.99	1.98	1.65								
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00								
Mg	0.86	0.82	0.82	0.92	1.03	0.81	0.78	0.73	0.62	0.50	0.36								
Ca	0.50	0.57	0.57	0.42	0.23	0.11	0.11	0.11	0.11	0.11	0.13								
Mn	0.10	0.11	0.11	0.08	0.05	0.05	0.05	0.06	0.08	0.10	0.15								
Fe	1.55	1.53	1.53	1.61	1.71	2.06	2.11	2.18	2.27	2.38	3.24								
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03								
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00								

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Oxides	Sample		2		2		2		2		2		2		2		2	
	Region	R ₄	66	R ₄	67	R ₄	83	R ₄	84	*R ₄ @80	*R ₄ @80	R ₄	86	R ₄	87	*R ₄ @94	*R ₄ @94	R ₄
Point#		66	67	67	67	83	83	84	84	85	85	86	86	87	88	89	90	90
SiO ₂		15.4	29.9	35.6	36.1	36.3	36.9	36.4	36.7	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9	36.9
TiO ₂		0.74	0.86	0.03	0.05	0.03	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.04	0.04	0.09
Al ₂ O ₃		8.5	16.2	20.6	21.1	21.1	21.9	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	20.7
Cr ₂ O ₃		0.03	0.04	0.00	0.04	0.00	0.06	0.03	0.00	0.03	0.03	0.06	0.06	0.03	0.00	0.00	0.00	0.04
MgO		5.80	11.05	3.34	4.00	4.69	7.45	4.49	4.29	4.49	4.49	7.45	7.45	4.49	4.29	3.90	3.90	3.90
CaO		0.11	0.04	1.18	1.18	1.16	1.09	1.18	1.14	1.18	1.18	1.09	1.09	1.18	1.14	1.09	1.09	0.95
MnO		0.17	0.04	1.95	1.58	1.25	0.66	1.55	1.57	1.55	1.55	0.66	0.66	1.55	1.57	1.70	1.70	1.48
FeO		17.5	15.0	35.2	35.0	34.0	31.3	34.6	34.5	34.6	34.6	31.3	31.3	34.6	34.5	35.0	35.0	28.7
Na ₂ O		0.38	0.35	0.01	0.01	0.00	0.02	0.01	0.00	0.01	0.01	0.02	0.02	0.01	0.00	0.02	0.02	0.04
Total		48.7	73.5	97.9	99.0	98.4	99.5	99.7	99.6	99.7	99.7	99.5	99.5	99.7	99.6	100.0	100.0	90.4

Cations Based on 12 Oxygens

Si	2.50	3.01	2.93	2.93	2.94	2.90	2.92	2.95	2.96	3.00
Ti	0.09	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Al	1.63	1.92	2.00	2.01	2.02	2.03	2.02	2.03	2.02	2.13
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.40	1.66	0.41	0.48	0.57	0.87	0.54	0.51	0.47	0.51
Ca	0.02	0.01	0.11	0.10	0.10	0.09	0.10	0.10	0.09	0.09
Mn	0.02	0.00	0.14	0.11	0.09	0.04	0.11	0.11	0.12	0.11
Fe	2.22	1.26	2.41	2.36	2.29	2.05	2.31	2.31	2.34	2.09
Na	0.12	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.94

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Oxides	Sample		2		2		2		2		2		2		2		2	
	Region	R ₄	R ₄	100	R ₄	101	R ₄	102	R ₄	103	*R ₄ @98	R ₄	105	**R ₄ @110	R ₄	107	R ₄	116
SiO ₂		31.8	32.1		32.3		35.4		35.9		38.4		38.3		38.8		44.0	41.5
TiO ₂		0.42	0.35		0.04		0.02		0.05		0.02		0.00		0.00		0.00	0.01
Al ₂ O ₃		18.3	18.3		19.0		20.8		21.0		22.0		22.0		22.9		28.5	21.6
Cr ₂ O ₃		0.03	0.00		0.02		0.00		0.02		0.05		0.00		0.00		0.01	0.01
MgO		11.89	11.06		3.18		3.35		4.16		8.70		8.69		8.52		2.25	5.71
CaO		0.16	0.28		1.04		1.06		1.07		3.46		3.49		3.34		2.47	4.19
MnO		0.02	0.43		1.99		1.95		1.49		0.99		0.93		0.90		0.17	0.76
FeO		14.9	19.1		34.5		35.7		35.1		26.2		26.2		24.7		6.0	18.8
Na ₂ O		0.28	0.25		0.03		0.00		0.02		0.02		0.01		0.05		1.21	2.02
Total		77.8	81.8		92.1		98.3		98.7		99.8		99.6		99.3		84.6	94.6

Cations Based on 12 Oxygens

Si	3.00	2.94	2.85	2.91	2.92	2.96	2.96	2.99	3.50	3.27
Ti	0.03	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.03	1.97	1.98	2.02	2.01	2.00	2.00	2.08	2.68	2.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.67	1.51	0.42	0.41	0.50	1.00	1.00	0.98	0.27	0.67
Ca	0.02	0.03	0.10	0.09	0.09	0.29	0.29	0.28	0.21	0.35
Mn	0.00	0.03	0.15	0.14	0.10	0.07	0.06	0.06	0.01	0.05
Fe	1.18	1.45	2.50	2.43	2.37	1.68	1.68	1.59	0.40	1.23
Na	0.05	0.04	0.01	0.00	0.00	0.00	0.00	0.01	0.19	0.31
Total	7.98	8.00	8.00	8.00	8.00	8.00	8.00	7.98	7.25	7.89

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Oxides	Sample		2		2		2		2		2		2		2		2		2	
	Region	Point#	**R ₄ @114	**R ₄ @114	**R ₄ @114	**R ₄ @114	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₃
			117 r	119 r	120 r	115 r	116 r	117 r	118 r	119 r	120 r	120 r	120 r	120 r	120 r	120 r	120 r	120 r	120 r	131 m
SiO ₂		38.0	37.9	38.7	52.0	36.9	38.1	37.8	38.1	37.8	38.1	37.8	38.1	37.8	38.1	37.8	38.1	37.8	38.1	48.2
TiO ₂		0.02	0.03	0.02	0.00	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.00
Al ₂ O ₃		21.8	21.8	22.2	25.0	21.2	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	21.7	24.1
Cr ₂ O ₃		0.02	0.03	0.03	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO		8.70	8.59	8.71	0.19	7.82	8.43	8.59	8.48	8.59	8.48	8.59	8.48	8.59	8.48	8.59	8.48	8.59	8.48	4.24
CaO		3.53	3.48	3.47	5.60	3.27	3.42	3.46	3.45	3.46	3.45	3.46	3.45	3.46	3.45	3.46	3.45	3.46	3.45	6.43
MnO		1.04	1.07	0.78	0.01	0.89	0.94	1.04	1.05	1.04	1.05	1.04	1.05	1.04	1.05	1.04	1.05	1.04	1.05	0.63
FeO		25.7	26.0	25.8	1.1	24.4	25.5	25.7	25.5	25.7	25.5	25.7	25.5	25.7	25.5	25.7	25.5	25.7	25.5	10.6
Na ₂ O		0.02	0.00	0.00	5.73	0.16	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.03	0.01	4.27
Total		98.9	98.9	99.8	89.6	94.7	98.0	98.3	98.0	98.3	98.0	98.3	98.0	98.3	98.0	98.3	98.0	98.3	98.0	98.5

Cations Based on 12 Oxygens

Si	2.96	2.95	2.98	3.88	2.99	2.99	2.99	2.96	2.98	2.98	2.98	2.96	2.98	2.98	2.98	2.96	2.98	2.98	2.98	3.49
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.00	2.01	2.02	2.20	2.03	2.03	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.01	2.02	2.02	2.02	2.06	2.06
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	1.01	1.00	1.00	0.02	0.95	0.95	0.99	1.00	0.99	1.00	0.99	1.00	0.99	1.00	0.99	0.99	0.99	0.99	0.99	0.46
Ca	0.29	0.29	0.29	0.45	0.28	0.28	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.50
Mn	0.07	0.07	0.05	0.00	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.04
Fe	1.67	1.68	1.66	0.07	1.66	1.66	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.67	1.66	1.66	1.66	1.66	1.66	0.64
Na	0.00	0.00	0.00	0.83	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60
Total	8.00	8.00	8.00	7.44	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.78

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core.

Appendix 4b; Sample 2 Garnet

Sample	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Region	**R ₂ @156	**R ₂ @156	**R ₂ @163	**R ₂ @167	R ₁	**R ₁ @172	**R ₁ @174	**R ₁ @175	**R ₁ @176	**R ₁ @177	**R ₁ @179	**R ₁ @181					
Oxides	Point#	161	162	164	170	171 c	173 c	174 c	175 c	176 c	177 c	182 c					
SiO ₂	37.9	38.1	37.8	37.2	37.5	37.4	37.4	37.4	37.5	37.5	37.7	37.7	37.7	37.7	37.7	37.7	37.7
TiO ₂	0.58	0.41	0.33	0.87	0.50	0.40	0.40	0.14	0.14	0.11	0.12	0.08	0.12	0.12	0.12	0.08	0.08
Al ₂ O ₃	21.6	21.7	21.5	21.1	21.2	21.3	21.3	21.1	21.3	21.2	22.8	21.3	22.8	22.8	22.8	21.3	21.3
Cr ₂ O ₃	0.01	0.00	0.04	0.01	0.02	0.05	0.05	0.02	0.04	0.00	0.04	0.00	0.04	0.04	0.04	0.00	0.00
MgO	6.79	6.85	7.19	3.82	3.86	3.85	3.85	3.95	3.98	3.91	3.24	3.88	3.24	3.24	3.24	3.88	3.88
CaO	4.89	4.85	4.78	8.53	8.70	8.68	8.68	8.89	8.73	8.83	9.12	8.76	9.12	9.12	9.12	8.76	8.76
MnO	1.55	1.75	1.60	4.66	4.74	4.71	4.71	4.58	4.43	4.69	4.12	4.58	4.12	4.12	4.12	4.58	4.58
FeO	26.6	26.1	25.8	23.1	23.3	23.0	23.0	22.8	23.0	22.8	20.4	23.2	20.4	20.4	20.4	23.2	23.2
Na ₂ O	0.02	0.01	0.00	0.02	0.02	0.00	0.00	0.02	0.01	0.01	0.10	0.00	0.10	0.10	0.10	0.00	0.00
Total	99.9	99.8	99.1	99.3	99.9	99.3	99.3	98.9	99.1	99.1	97.6	99.5	97.6	97.6	97.6	99.5	99.5

Cations Based on 12 Oxygens

Si	2.95	2.97	2.96	2.95	2.95	2.96	2.96	2.97	2.97	2.98	2.99	2.98	2.99	2.99	2.99	2.98	2.98
Ti	0.03	0.02	0.02	0.05	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.00	0.00
Al	1.99	1.99	1.99	1.97	1.97	1.99	1.99	1.98	1.99	1.98	2.13	1.98	2.13	2.13	2.13	1.98	1.98
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.79	0.80	0.84	0.45	0.45	0.45	0.45	0.47	0.47	0.46	0.38	0.46	0.38	0.38	0.38	0.46	0.46
Ca	0.41	0.40	0.40	0.73	0.74	0.74	0.74	0.76	0.74	0.75	0.78	0.74	0.78	0.78	0.78	0.74	0.74
Mn	0.10	0.12	0.11	0.31	0.32	0.32	0.32	0.31	0.30	0.32	0.28	0.31	0.28	0.28	0.28	0.31	0.31
Fe	1.73	1.70	1.68	1.53	1.53	1.52	1.52	1.50	1.52	1.51	1.36	1.53	1.36	1.36	1.36	1.53	1.53
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.02	0.02	0.00	0.00
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.94	8.00	7.94	7.94	7.94	8.00	8.00

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₁ = Rim; R₂ = Mantle; R₃ = OuterCore; R₄ = Core;

Appendix 4c: Sample 3 Garnet Electron Microprobe Analyses

Appendix 4c; Sample 3 Garnet

Oxides	Sample			3			3			3			3			3		
	Position	R ₃	R ₂	R ₂	R ₂	R ₂	R ₁	R ₂	R ₂	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁
	Point#	25	26	27	28	29	30	32	33	34	35	36	37	38	39	40	41	42
SiO ₂		38.2	37.5	36.9	36.9	37.4	37.6	37.6	37.6	37.8	27.8							
TiO ₂		0.01	0.06	0.08	0.08	0.07	0.02	0.02	0.48	0.16	13.20							
Al ₂ O ₃		21.9	21.5	21.0	21.1	21.2	21.2	21.5	21.6	21.6	16.3							
Cr ₂ O ₃		0.02	0.01	0.00	0.01	0.00	0.00	0.02	0.00	0.01	0.02							
MgO		8.84	6.05	3.41	4.35	5.16	5.94	5.61	5.73	5.90	4.13							
CaO		2.86	6.14	7.70	6.11	4.90	3.66	3.03	3.27	3.25	2.29							
MnO		0.85	1.93	3.69	3.91	3.51	2.83	3.01	2.91	2.94	2.72							
FeO		26.8	26.0	25.9	26.4	27.3	28.2	29.3	28.8	28.6	33.3							
Na ₂ O		0.00	0.02	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.02							
Total		99.6	99.2	98.8	98.8	99.5	99.5	100.5	100.1	100.2	99.7							

Cations Based on 12 Oxygens

Si	2.96	2.95	2.96	2.95	2.96	2.96	2.97	2.95	2.96	2.96	2.33							
Ti	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.03	0.01	0.01	0.83							
Al	2.00	1.99	1.99	1.99	1.98	1.98	1.98	1.99	2.00	2.00	1.60							
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
Mg	1.02	0.71	0.41	0.52	0.61	0.61	0.70	0.66	0.67	0.69	0.52							
Ca	0.24	0.52	0.66	0.52	0.42	0.42	0.31	0.26	0.28	0.27	0.21							
Mn	0.06	0.13	0.25	0.26	0.24	0.24	0.19	0.20	0.19	0.20	0.19							
Fe	1.73	1.70	1.73	1.75	1.80	1.80	1.85	1.92	1.89	1.87	2.32							
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00							
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00							

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₄ = Rim; R₃ = Mantle; R₂ = OuterCore; R₁ = Core;

Appendix 4c; Sample 3 Garnet

Oxides	Sample 3			3			3			3			3			3														
	Position			*R _i @39			**R _i @42			**R _i @42			**R _i @46			**R _i @54			**R _i @60			**R _i @60			**R _i @64			**R _i @69		
	Point#			41	43	44	45	56	57	58	59	66	67																	
SiO ₂	37.8	37.3	37.4	37.8	37.4	37.8	37.4	37.8	37.6	52.7	37.7	37.8																		
TiO ₂	0.18	0.28	0.21	0.04	0.00	0.00	0.00	0.00	0.00	0.02	0.04	0.02																		
Al ₂ O ₃	21.6	21.2	21.3	21.6	21.4	21.5	21.5	21.5	21.5	23.7	21.7	21.4																		
Cr ₂ O ₃	0.02	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.04																		
MgO	5.78	5.74	5.78	5.93	5.48	6.49	6.34	6.49	6.34	0.96	6.56	6.55																		
CaO	3.32	3.30	3.29	4.09	4.16	3.07	3.15	3.07	3.15	5.91	3.03	3.08																		
MnO	2.96	3.00	2.98	2.90	3.09	2.68	2.46	2.68	2.46	0.64	2.49	2.52																		
FeO	28.6	28.4	28.4	27.9	27.9	28.1	27.7	28.1	27.7	7.1	28.3	28.0																		
Na ₂ O	0.00	0.00	0.02	0.00	0.02	0.00	0.05	0.00	0.05	6.02	0.01	0.01																		
Total	100.2	99.2	99.4	100.2	99.4	99.7	98.8	99.7	98.8	97.0	99.8	99.5																		

Cations Based on 12 Oxygens

Si	2.96	2.96	2.96	2.96	2.96	2.97	2.98	3.78	2.96	2.97
Ti	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	2.00	1.99	1.99	1.99	2.00	1.99	2.00	2.01	2.01	1.99
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.68	0.68	0.68	0.69	0.65	0.76	0.75	0.10	0.77	0.77
Ca	0.28	0.28	0.28	0.34	0.35	0.26	0.27	0.45	0.25	0.26
Mn	0.20	0.20	0.20	0.19	0.21	0.18	0.17	0.04	0.17	0.17
Fe	1.87	1.88	1.87	1.82	1.83	1.84	1.83	0.42	1.84	1.84
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.84	0.00	0.00
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	7.64	8.00	8.00

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R_i = Rim; R_m = Mantle; R_o = OuterCore; R_c = Core;

Appendix 4c: Sample 3 Garnet

Oxides	Sample 3		3		3		3		3		3		3		3		3		3	
	Position	Point#	**R ₁ @69	**R ₁ @73	**R ₁ @75	**R ₁ @77	**R ₁ @77	**R ₁ @83	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂
SiO ₂		68	37.6	38.0	37.6	37.5	37.8	37.8	38.4	38.5	38.3	38.3	38.1	38.3	38.3	38.3	38.3	38.3	38.3	38.3
TiO ₂			0.02	0.01	0.01	0.03	0.01	0.01	0.04	0.01	0.03	0.03	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Al ₂ O ₃			21.6	21.8	21.4	21.3	21.7	21.7	21.5	21.7	21.6	21.6	21.7	21.6	21.6	21.6	21.6	21.6	21.6	21.6
Cr ₂ O ₃			0.00	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO			6.47	6.87	6.87	6.81	7.25	7.25	7.13	7.37	7.43	7.43	7.61	7.47	7.47	7.47	7.47	7.47	7.47	7.47
CaO			3.19	3.17	3.11	3.01	3.09	3.09	2.98	3.02	2.98	2.98	3.14	4.19	4.19	4.19	4.19	4.19	4.19	4.19
MnO			2.52	2.39	2.30	2.29	2.08	2.08	2.42	2.14	2.16	2.16	2.09	1.71	1.71	1.71	1.71	1.71	1.71	1.71
FeO			27.9	27.7	27.8	27.9	27.4	27.4	27.7	27.6	27.2	27.2	27.1	26.5	26.5	26.5	26.5	26.5	26.5	26.5
Na ₂ O			0.00	0.00	0.01	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total			99.2	100.0	99.2	98.8	99.4	99.4	100.1	100.3	99.7	99.7	99.8	99.8	99.8	99.8	99.8	99.8	99.8	99.8

Cations Based on 12 Oxygens																				
Si	2.97	2.97	2.96	2.96	2.96	2.97	2.96	2.96	2.99	2.99	2.99	2.99	2.97	2.98						
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
Al	2.00	2.01	1.99	1.99	1.99	1.99	2.00	2.00	1.98	1.99	1.99	1.99	1.99	1.99						
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
Mg	0.76	0.80	0.81	0.80	0.81	0.80	0.85	0.85	0.83	0.85	0.86	0.86	0.89	0.87						
Ca	0.27	0.27	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25	0.25	0.25	0.26	0.35						
Mn	0.17	0.16	0.15	0.15	0.15	0.15	0.14	0.14	0.16	0.14	0.14	0.14	0.14	0.11						
Fe	1.83	1.81	1.82	1.84	1.82	1.84	1.79	1.79	1.80	1.79	1.78	1.78	1.77	1.72						
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00						
Total	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.02	8.02	8.01	8.01	8.03	8.02						

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₁ = Rim; R₂ = Mantle; R₃ = OuterCore; R₄ = Core;

Appendix 4c; Sample 3 Garnet

Oxides	Sample			3			3			3			3			3			3			3		
	Position	R ₃	R ₃	R ₃	R ₃	R ₃	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄
Point#	97	98	99	100	101	102	104	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128
SiO ₂	38.4	38.3	37.9	38.8	39.0	38.9	37.7	53.7	47.6	38.4														
TiO ₂	0.03	0.74	0.24	0.04	0.05	0.03	0.02	0.01	0.01	0.02														
Al ₂ O ₃	21.8	21.6	21.9	22.1	22.0	22.0	21.3	27.2	23.9	21.5														
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00														
MgO	8.10	8.74	9.14	9.83	10.08	9.98	6.24	0.01	1.38	7.46														
CaO	4.64	3.60	3.00	1.85	1.25	1.21	1.28	10.96	8.02	4.70														
MnO	1.31	1.03	0.90	0.86	0.80	0.71	1.21	0.05	0.38	1.32														
FeO	25.3	25.4	26.1	26.6	26.8	26.4	31.9	0.4	7.3	25.2														
Na ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00														
Total	99.5	99.5	99.2	100.0	99.9	99.2	99.6	92.3	88.5	98.6														

Cations Based on 12 Oxygens

Si	2.98	2.97	2.95	2.98	2.99	3.00	2.99	3.84	3.70	3.01														
Ti	0.00	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00														
Al	1.99	1.97	2.00	2.00	1.99	2.00	1.99	2.30	2.19	1.98														
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00														
Mg	0.94	1.01	1.06	1.12	1.15	1.15	0.74	0.00	0.16	0.87														
Ca	0.39	0.30	0.25	0.15	0.10	0.10	0.11	0.84	0.67	0.39														
Mn	-0.09	0.07	0.06	0.06	0.05	0.05	0.08	-0.00	0.03	0.09														
Fe	1.64	1.65	1.70	1.71	1.72	1.70	2.12	0.02	0.47	1.65														
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00														
Total	8.02	8.00	8.03	8.02	8.01	8.00	8.02	7.01	7.21	8.00														

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₃ = Rim; R₄ = Mantle; R₅ = OuterCore; R₆ = Core;

Appendix 4c; Sample 3 Garnet

Oxides	Sample											
	Position											
	Point#	3 115	3 116	3 117	3 118	3 119	3 120	3 122	3 123	3 124	3 125	
SiO ₂		38.3	38.5	38.4	38.3	38.5	38.5	39.0	38.7	38.7	38.5	
TiO ₂		0.03	0.02	0.03	0.04	0.04	0.01	0.04	0.04	0.06	0.04	
Al ₂ O ₃		21.4	21.6	21.5	21.4	21.5	21.5	21.9	21.8	21.7	21.7	
Cr ₂ O ₃		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
MgO		7.81	7.66	7.80	7.83	7.73	7.67	7.11	7.29	7.39	7.41	
CaO		4.81	4.74	4.73	4.54	4.63	4.71	4.94	4.77	4.83	4.92	
MnO		1.30	1.30	1.27	1.35	1.23	1.31	1.37	1.35	1.38	1.46	
FeO		25.5	25.4	25.3	25.2	25.4	25.3	25.8	25.7	25.6	25.8	
Na ₂ O		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Total		99.1	99.3	99.2	98.6	99.0	99.0	100.2	99.6	99.6	99.9	

Cations Based on 12 Oxygens

Si	2.99	3.00	3.00	3.00	3.00	3.00	3.00	3.01	3.01	3.00	2.99
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.97	1.98	1.98	1.98	1.98	1.98	1.98	1.99	1.99	1.98	1.99
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.91	0.89	0.91	0.91	0.91	0.90	0.89	0.82	0.84	0.86	0.86
Ca	0.40	0.40	0.40	0.38	0.39	0.39	0.39	0.41	0.40	0.40	0.41
Mn	0.09	0.09	0.08	0.09	0.08	0.08	0.09	0.09	0.09	0.09	0.10
Fe	1.66	1.66	1.65	1.65	1.65	1.65	1.65	1.66	1.66	1.66	1.67
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	0.00
Total	8.02	8.01	8.01	8.01	8.01	8.00	8.01	7.99	7.99	8.00	8.01

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₁ = Rim; R₂ = Mantle; R₃ = OuterCore; R₄ = Core;

Appendix 4c: Sample 3 Garnet

Oxides	Sample 3															
	Position	**R ₃ @127	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132	**R ₂ @132
	Point#	126	137	138	139	140	141	150	151	152	153	154	155	156	157	158
SiO ₂		38.8	38.5	38.2	37.9	38.0	37.7	44.8	36.5	37.7	37.8					
TiO ₂		0.04	0.05	0.06	0.03	0.05	0.04	0.01	0.04	0.04	0.07					
Al ₂ O ₃		21.8	21.4	21.3	21.2	21.5	21.4	23.9	20.6	21.1	21.2					
Cr ₂ O ₃		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
MgO		7.55	4.93	5.01	5.11	5.05	5.12	2.24	5.01	5.06	5.06					
CaO		4.84	5.29	5.10	4.95	4.98	4.88	7.69	5.08	5.26	5.33					
MnO		1.43	3.19	3.37	3.32	3.24	3.37	1.40	3.20	3.34	3.31					
FeO		25.3	26.7	26.6	26.5	27.0	26.9	13.0	26.2	26.8	27.3					
Na ₂ O		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Total		99.7	100.0	99.6	99.0	99.8	99.4	93.0	96.7	99.3	100.0					

Cations Based on 12 Oxygens

Si	3.00	3.02	3.01	3.01	3.01	3.00	2.98	3.46	2.98	2.99	2.99					
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Al	1.99	1.98	1.98	1.99	2.00	2.00	2.00	2.17	1.98	1.98	1.97					
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Mg	0.87	0.58	0.59	0.60	0.59	0.59	0.60	0.26	0.61	0.60	0.60					
Ca	0.40	0.44	0.43	0.42	0.42	0.42	0.41	0.64	0.44	0.45	0.45					
Mn	0.09	0.21	0.22	0.22	0.22	0.22	0.23	0.09	0.22	0.22	0.22					
Fe	1.64	1.75	1.75	1.76	1.78	1.78	1.78	0.84	1.79	1.78	1.80					
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Total	8.00	7.99	7.99	8.00	8.00	8.00	8.01	7.46	8.03	8.02	8.03					

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₁ = Rim; R₂ = Mantle; R₃ = OuterCore; R₄ = Core;

Appendix 4c; Sample 3 Garnet

Oxides	Sample 3			3			3			3			3			3			R ₂ 169b
	Position	**R ₂ @143	**R ₂ @143	**R ₂ @143	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	**R ₁ @157	
	Point#	154	155	156	164	165	166	167	168	169a	169a	169a	169a	169a	169a	169a	169a	169a	
SiO ₂		37.8	37.8	37.9	55.3	39.4	37.6	38.0	37.8	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	37.9	46.3
TiO ₂		0.05	0.04	0.08	0.00	0.00	0.02	0.01	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05
Al ₂ O ₃		21.2	21.1	21.2	24.3	19.1	21.0	21.1	21.2	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	21.1	20.8
Cr ₂ O ₃		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
MgO		5.05	5.00	5.03	0.44	2.53	5.11	5.06	5.10	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.09	5.51
CaO		5.37	5.32	5.29	6.99	5.34	4.97	4.86	4.81	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	4.70	2.08
MnO		3.36	3.47	3.31	0.09	1.30	3.15	3.17	3.16	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	3.37	1.56
FeO		26.8	27.1	27.0	1.3	12.8	26.9	26.9	27.2	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	27.1	20.1
Na ₂ O		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28
Total		99.7	99.8	99.8	88.4	80.5	98.7	99.1	99.3	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	99.4	96.6

Cations Based on 12 Oxygens

Si	2.99	2.99	2.99	2.99	4.08	3.53	3.00	3.01	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.51
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.98	1.97	1.97	1.97	2.11	2.02	1.97	1.97	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.86
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.60	0.59	0.59	0.59	0.05	0.34	0.61	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.62
Ca	0.45	0.45	0.45	0.45	0.55	0.51	0.42	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.17
Mn	0.23	0.23	0.23	0.22	0.01	0.10	0.21	0.21	0.21	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.10
Fe	1.78	1.79	1.78	1.78	0.08	0.96	1.80	1.79	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.27
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04
Total	8.02	8.02	8.02	8.02	6.87	7.46	8.01	8.00	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	7.58

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₁ = Rim; R₂ = Mantle; R₃ = OuterCore; R₄ = Core;

Appendix 4c; Sample 3 Garnet

Sample	3	3	3	3	3	3	3	3	3	3	3	3	3
Position	R ₂	@Ksp172b	R ₂	@Ksp172b	R ₁	@Ksp177	R ₁	@Ksp177	R ₁	@Ksp177	R ₁	@Ksp177	R ₂
Oxides	Point#	170	171	172	181	182	183	184	185	186	187	188	189
SiO ₂	38.9	39.1	55.1	38.7	38.8	38.6	38.5	38.8	39.1	39.0			
TiO ₂	0.04	0.00	0.01	0.02	0.02	0.02	0.00	0.04	0.06	0.06			
Al ₂ O ₃	21.5	21.7	20.1	21.4	21.4	21.4	21.9	21.4	21.5	21.6			
Cr ₂ O ₃	0.04	0.01	0.01	0.04	0.07	0.04	0.00	0.00	0.00	0.00			
MgO	7.75	7.72	3.28	7.35	7.22	7.26	7.07	7.48	7.91	7.96			
CaO	2.89	2.96	1.14	2.76	2.91	2.98	2.69	2.95	2.90	2.82			
MnO	2.03	2.21	1.06	2.31	2.22	2.31	2.01	2.36	2.01	1.97			
FeO	27.0	27.0	12.3	27.9	27.6	27.6	26.7	28.0	27.3	27.5			
Na ₂ O	0.02	0.01	0.54	0.01	0.00	0.02	0.01	0.00	0.04	0.03			
Total	100.2	100.6	93.5	100.5	100.1	100.3	98.8	101.0	100.7	100.9			

Cations Based on 12 Oxygens	3	3	3	3	3	3	3	3	3	3	3	3	3
Si	3.01	3.01	4.04	3.01	3.02	3.00	3.02	3.00	3.01	3.00			
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Al	1.97	1.97	1.73	1.96	1.96	1.96	2.02	1.95	1.95	1.96			
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			
Mg	0.90	0.89	0.36	0.85	0.84	0.84	0.83	0.86	0.91	0.91			
Ca	0.24	0.24	0.09	0.23	0.24	0.25	0.23	0.24	0.24	0.23			
Mn	0.13	0.14	0.07	0.15	0.15	0.15	0.13	0.15	0.13	0.13			
Fe	1.75	1.74	0.75	1.81	1.79	1.80	1.75	1.81	1.76	1.77			
Na	0.00	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.01	0.00			
Total	8.00	8.00	7.13	8.01	8.00	8.01	7.98	8.02	8.01	8.02			

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₁ = Rim; R₂ = Mantle; R₃ = OuterCore; R₄ = Core.

Appendix 4c; Sample 3 Garnet

Appendix 1: Sample 3 - Grt1c1																
Sample		3			3			3			3			3		
Position		R ₃			R ₃			R ₃			R ₃			R ₃		
Oxides	Point#	202	203	204	205	215	216	217	218	222	223	223	223	223		
SiO ₂		38.8	39.1	38.8	38.9	37.4	38.1	38.2	38.3	38.7	39.0					
TiO ₂		0.02	0.04	0.00	0.02	0.06	0.02	0.03	0.03	0.00	0.00					
Al ₂ O ₃		21.8	21.7	21.8	21.7	20.8	21.3	21.6	21.6	21.6	21.8					
Cr ₂ O ₃		0.04	0.02	0.00	0.03	0.00	0.01	0.04	0.00	0.00	0.03					
MgO		7.74	7.98	8.22	8.27	7.68	8.08	8.25	8.45	8.98	8.79					
CaO		2.18	2.43	2.51	2.62	2.20	2.44	2.59	2.71	2.19	2.38					
MnO		1.43	1.52	1.62	1.47	1.34	1.52	1.57	1.51	1.46	1.38					
FeO		28.4	27.5	26.9	27.1	27.9	27.3	27.3	26.6	26.6	26.3					
Na ₂ O		0.02	0.01	0.03	0.03	0.02	0.01	0.00	0.01	0.00	0.01					
Total		100.5	100.3	99.9	100.1	97.3	98.8	99.7	99.2	99.6	99.7					

Cations Based on 12 Oxygens

Si	3.00	3.02	3.00	3.00	3.00	2.99	3.00	2.98	2.99	3.00	3.01		
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Al	1.99	1.98	1.99	1.98	1.96	1.96	1.97	1.99	1.99	1.97	1.98		
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Mg	0.89	0.92	0.95	0.95	0.92	0.92	0.95	0.96	0.98	1.04	1.01		
Ca	0.18	0.20	0.21	0.22	0.19	0.19	0.21	0.22	0.23	0.18	0.20		
Mn	0.09	0.10	0.11	0.10	0.09	0.09	0.10	0.10	0.10	0.10	0.09		
Fe	1.83	1.78	1.74	1.75	1.87	1.87	1.79	1.78	1.73	1.73	1.70		
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Total	8.00	7.99	8.00	8.01	8.03	8.03	8.02	8.03	8.02	8.01	8.00		

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₃ = Rim; R₂ = Mantle; R₁ = Outer Core; R₀ = Core.

Appendix 4c; Sample 3 Garnet

Oxides	Sample		3		3		3		3		3		3		3		3		3	
	Position	Point#	R ₃	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄
		224	224	225	226	227	228	229	242	243	244	245								
SiO ₂		38.7	38.4	0.00	0.01	0.00	0.04	0.02	0.03	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TiO ₂		0.03	0.00	0.00	0.01	0.00	0.04	0.02	0.03	0.03	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ₂ O ₃		21.8	21.5	0.01	0.01	0.01	0.03	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr ₂ O ₃		0.02	0.01	0.01	0.01	0.01	0.03	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO		8.69	7.65	0.01	0.01	0.01	0.03	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO		2.53	1.56	0.01	0.01	0.01	0.03	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MnO		1.44	0.82	0.01	0.01	0.01	0.03	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO		26.4	30.1	0.02	0.02	0.00	0.04	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Na ₂ O		0.03	0.02	0.00	0.00	0.00	0.02	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		99.6	100.0	100.0	99.8	99.1	99.9	99.5	99.0	99.8	100.0	99.7								

Cations Based on 12 Oxygens		3		3		3		3		3		3		3		3		3		3	
		R ₃	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄	*@Bt230	R ₄
		224	225	226	227	228	229	242	243	244	245										
Si		3.00	3.00	3.00	2.99	2.99	3.00	3.00	3.00	3.00	2.98										
Ti		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00										
Al		1.99	1.98	1.98	1.99	1.98	1.98	1.98	1.99	1.97	2.00										
Cr		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00										
Mg		1.00	0.89	0.82	0.73	0.64	0.56	0.56	0.54	0.58	0.63										
Ca		0.21	0.13	0.14	0.13	0.13	0.13	0.13	0.11	0.10	0.11										
Mn		0.09	0.05	0.07	0.07	0.09	0.10	0.10	0.10	0.10	0.09										
Fe		1.71	1.96	2.01	2.09	2.19	2.24	2.24	2.25	2.23	2.20										
Na		0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00										
Total		8.01	8.02	8.01	8.01	8.02	8.01	8.01	8.00	8.01	8.01										

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₃ = Rim; R₄ = Mantle; R₅ = OuterCore; R₆ = Core.

Appendix 4c; Sample 3 Garnet

Sample	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
*@Bt239	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248	*@Bt248
R ₄	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂
246	250	251	252	252	252	252	252	252	252	252	260	261	262	262	262	263	263	263	263	263	263	269	270
Oxides	Point#																						
SiO ₂	38.1	37.4	38.0	38.1	38.1	38.1	38.1	38.1	38.1	38.1	44.2	38.5	38.4	38.4	38.4	38.3	38.3	38.3	38.3	38.3	38.3	41.4	38.1
TiO ₂	0.04	0.14	0.12	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.03	0.06	0.05	0.05	0.05	0.07	0.07	0.07	0.07	0.07	0.07	0.01	0.09
Al ₂ O ₃	21.4	20.9	21.1	21.2	21.2	21.2	21.2	21.2	21.2	21.2	25.9	21.4	21.3	21.3	21.3	21.4	21.4	21.4	21.4	21.4	21.4	23.7	21.2
Cr ₂ O ₃	0.02	0.06	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03
MgO	6.16	4.01	4.41	4.76	4.76	4.76	4.76	4.76	4.76	4.76	2.22	5.29	5.25	5.25	5.25	5.39	5.39	5.39	5.39	5.39	5.39	3.64	5.94
CaO	1.20	5.05	5.29	5.31	5.31	5.31	5.31	5.31	5.31	5.31	5.53	5.00	5.01	5.01	5.01	4.91	4.91	4.91	4.91	4.91	4.91	8.85	6.74
MnO	1.17	3.47	3.41	3.08	3.08	3.08	3.08	3.08	3.08	3.08	1.02	3.09	3.04	3.04	3.04	3.27	3.27	3.27	3.27	3.27	3.27	1.35	2.14
FeO	31.7	28.9	27.7	27.6	27.6	27.6	27.6	27.6	27.6	27.6	10.4	26.2	26.7	26.7	26.7	27.0	27.0	27.0	27.0	27.0	27.0	14.9	24.9
Na ₂ O	0.01	0.00	0.00	0.02	0.02	0.02	0.02	0.02	0.02	0.02	1.75	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	1.43	0.02
Total	99.8	99.9	100.0	100.2	100.2	100.2	100.2	100.2	100.2	100.2	91.1	99.7	99.9	99.9	99.9	100.3	100.3	100.3	100.3	100.3	95.3	95.3	99.2
Cations Based on 12 Oxygens																							
Si	3.01	2.98	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.43	3.02	3.02	3.02	3.02	3.00	3.00	3.00	3.00	3.00	3.22	3.00	
Ti	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	
Al	1.99	1.97	1.96	1.97	1.97	1.97	1.97	1.97	1.97	1.97	2.36	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	1.98	2.16	1.97	
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Mg	0.72	0.48	0.52	0.56	0.56	0.56	0.56	0.56	0.56	0.56	0.26	0.62	0.61	0.61	0.61	0.63	0.63	0.63	0.63	0.63	0.42	0.70	
Ca	0.10	0.43	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.46	0.42	0.42	0.42	0.41	0.41	0.41	0.41	0.41	0.41	0.74	0.57	
Mn	0.08	0.23	0.23	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.07	0.21	0.20	0.20	0.20	0.22	0.22	0.22	0.22	0.22	0.09	0.14	
Fe	2.09	1.93	1.83	1.82	1.82	1.82	1.82	1.82	1.82	1.82	0.68	1.72	1.76	1.76	1.76	1.77	1.77	1.77	1.77	1.77	0.97	1.64	
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	
Total	8.00	8.03	8.01	8.01	8.01	8.01	8.01	8.01	8.01	8.01	7.52	7.98	7.99	7.99	7.99	8.01	8.01	8.01	8.01	8.01	7.81	8.02	
* Used for thermometry; ** Used for barometry; All Fe reported as Fe ²⁺ ; R ₄ = Rim; R ₃ = Mantle; R ₂ = OuterCore; R ₁ = Core																							

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₄ = Rim; R₂ = Mantle; R₃ = OuterCore; R₁ = Core

Appendix 4c; Sample 3 Garnet

Oxides	Sample		3		3		3		3		3		3		3	
	Position	Point#	**@PI268	R ₂	**@PI268	R ₂	**@PI268	R ₂	@PI275	R ₂	@PI275	R ₂	@PI275	R ₂	@PI275	R ₂
SiO ₂			38.3		38.2		38.5		37.7		37.8		37.9		37.9	
TiO ₂			0.05		0.05		0.05		0.03		0.06		0.07		0.07	
Al ₂ O ₃			21.3		21.3		21.4		20.8		20.7		20.9		21.1	
Cr ₂ O ₃			0.00		0.04		0.04		0.00		0.02		0.04		0.02	
MgO			5.89		5.87		5.94		4.50		4.50		4.60		4.35	
CaO			6.62		6.66		6.56		6.16		6.02		6.01		6.00	
MnO			2.12		2.27		2.12		3.78		3.88		3.69		3.79	
FeO			25.0		25.0		25.2		26.1		25.9		26.6		26.4	
Na ₂ O			0.01		0.02		0.02		0.01		0.04		0.00		0.00	
Total			99.3		99.4		99.9		99.0		99.0		99.9		99.6	

Cations Based on 12 Oxygens

Si	3.01	3.00	3.01	3.00	3.00	3.01	3.00	3.01	3.00	3.00	3.01	3.00	3.00	3.00	3.00	3.00
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	1.97	1.97	1.97	1.97	1.97	1.97	1.97	1.95	1.96	1.95	1.95	1.95	1.95	1.95	1.97	1.97
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg	0.69	0.69	0.69	0.69	0.69	0.69	0.69	0.54	0.53	0.54	0.54	0.54	0.54	0.51	0.51	0.51
Ca	0.56	0.56	0.56	0.56	0.56	0.55	0.55	0.51	0.53	0.51	0.51	0.51	0.51	0.51	0.51	0.51
Mn	0.14	0.14	0.15	0.15	0.14	0.14	0.14	0.26	0.26	0.26	0.26	0.25	0.25	0.25	0.25	0.25
Fe	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.73	1.74	1.73	1.73	1.76	1.76	1.75	1.75	1.75
Na	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Total	8.01	8.02	8.02	8.02	8.01	8.01	8.02	8.01	8.02	8.01	8.01	8.02	8.02	8.01	8.01	8.01

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₂ = Rim; R₃ = Mantle;

R₂ = OuterCore; R₁ = Core.

Appendix 5a: Sample 1 Biotite Electron Microprobe Analyses

Appendix 5b: Sample 2 Biotite Electron Microprobe Analyses

Appendix 5b; Sample 2 Biotite

Oxide	Sample Position Point#	2 R ₄ *3@2	2 R ₄ *4@5	2 R ₄ *8@7	2 R ₄ *9@10	2 R ₄ 68	2 R ₄ 69	2 R ₄ 70	2 R ₄ 71	2 R ₄ *72@62	2 R ₄ *73@62	2 R ₄ 74	2 R ₄ 75	2 R ₄ 76
SiO ₂		36.6	37.0	36.6	36.4	29.4	12.4	23.9	31.7	35.2	35.8	30.7	35.9	35.7
TiO ₂		0.68	0.43	0.05	0.14	0.84	0.74	0.10	0.95	1.46	1.76	11.66	1.41	1.32
Al ₂ O ₃		19.8	19.9	20.3	20.0	16.0	6.75	14.0	17.2	19.1	19.2	16.8	18.8	19.1
MgO		15.2	15.4	14.8	14.9	11.0	4.52	2.27	12.0	13.0	13.1	11.0	13.4	13.2
CaO		0.07	0.03	0.02	0.03	0.05	0.15	1.11	0.03	0.08	0.11	0.01	0.01	0.00
MnO		0.00	0.00	0.04	0.07	0.07	0.25	1.68	0.05	0.00	0.03	0.03	0.00	0.02
FeO		12.1	12.2	12.3	12.0	14.7	16.4	33.1	14.5	14.3	13.9	12.8	14.2	14.5
Na ₂ O		0.33	0.33	0.40	0.34	0.39	0.36	0.04	0.37	0.29	0.32	0.31	0.31	0.31
K ₂ O		9.24	9.22	9.34	9.41	9.09	7.86	0.60	9.30	9.28	9.09	8.44	9.44	9.53
H ₂ O		3.74	3.66	3.71	3.76	3.04	1.45	2.91	3.31	3.76	3.70	3.48	3.70	3.67
F		0.59	0.83	0.63	0.50	0.63	0.57	0.00	0.55	0.30	0.53	0.76	0.51	0.56
Cl		0.05	0.06	0.07	0.07	0.09	0.08	0.02	0.07	0.09	0.09	0.07	0.08	0.11
Total		98.3	99.1	98.3	97.7	85.3	51.5	79.8	90.0	96.9	97.7	96.1	97.7	98.0
O=F		-0.25	-0.35	-0.27	-0.21	-0.27	-0.24	0.00	-0.23	-0.13	-0.22	-0.32	-0.22	-0.24
O=Cl		-0.01	-0.01	-0.02	-0.02	-0.02	-0.02	0.00	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Total		98.0	98.7	98.0	97.5	85.0	51.2	79.8	89.8	96.8	97.4	95.7	97.5	97.8

Cations Based on 24 Oxygens

Si	5.44	5.46	5.44	5.45	5.25	4.26	4.93	5.31	5.37	5.41	4.77	5.44	5.44	5.40
Ti	0.08	0.05	0.01	0.02	0.11	0.19	0.02	0.12	0.17	0.20	1.36	0.16	0.15	0.15
Al	3.46	3.46	3.56	3.53	3.36	2.74	3.40	3.38	3.44	3.42	3.08	3.35	3.40	3.40
Mg	3.36	3.38	3.29	3.32	2.92	2.32	0.70	2.98	2.97	2.94	2.55	3.02	2.99	2.99
Ca	0.01	0.00	0.00	0.01	0.01	0.05	0.25	0.01	0.01	0.01	0.02	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.01	0.01	0.07	0.29	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.50	1.50	1.53	1.50	2.20	4.71	5.69	2.03	1.83	1.76	1.67	1.80	1.80	1.83
Na	0.09	0.09	0.12	0.10	0.13	0.24	0.02	0.12	0.09	0.09	0.10	0.09	0.09	0.09
K	1.75	1.73	1.77	1.79	2.07	3.45	0.16	1.98	1.81	1.75	1.68	1.82	1.84	1.84
total	15.7	15.7	15.7	15.7	16.1	18.0	15.4	15.9	15.7	15.6	15.2	15.7	15.7	15.7
<H>	3.71	3.60	3.69	3.75	3.62	3.33	3.99	3.69	3.83	3.73	3.61	3.73	3.73	3.70
<F>	0.28	0.39	0.30	0.24	0.36	0.62	0.00	0.29	0.14	0.25	0.37	0.25	0.27	0.27
<Cl>	0.01	0.02	0.02	0.02	0.03	0.05	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.03
fm	0.31	0.31	0.32	0.31	0.43	0.67	0.90	0.41	0.38	0.38	0.40	0.37	0.37	0.38
Na+K	1.80	1.83	1.89	1.89	2.20	3.69	0.17	2.10	1.90	1.84	1.77	1.91	1.91	1.93

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₄ = Rim; R₃ = Mantle; R₂ = OuterCore; R₁ = Core.

Appendix 5c: Sample 3 Biotite Electron Microprobe Analyses

Appendix 5c; Sample 3 Biotite

Oxide	Sample Position Point#	3 18	3 R ₁ *@19 39	3 R ₃ *@202 192	3 R ₃ *@202 193	3 R ₃ *@202 194	3 R ₃ *@202 195	3 R ₃ *@202 196	3 R ₃ *@202 pt197	3 R ₃ *@202 198	3 R ₃ 206	3 R ₃ *@217 207
SiO ₂		37.8	37.4	39.3	39.4	39.2	39.6	39.5	41.5	42.2	39.1	38.3
TiO ₂		0.12	1.77	1.41	1.41	1.52	1.39	1.44	1.33	1.28	1.45	1.39
Al ₂ O ₃		21.5	18.4	18.4	18.5	18.4	18.3	18.4	17.7	17.5	18.6	19.0
MgO		5.70	18.5	19.7	19.6	19.4	19.4	19.8	19.2	19.2	19.6	19.4
CaO		1.03	0.01	0.00	0.02	0.01	0.05	0.02	0.04	0.04	0.01	0.00
MnO		1.15	0.04	0.00	0.00	0.04	0.05	0.00	0.05	0.04	0.01	0.02
FeO		30.3	9.42	7.35	7.51	7.35	7.52	7.30	7.14	7.11	7.15	7.47
Na ₂ O		0.06	0.45	0.47	0.46	0.47	0.44	0.45	0.44	0.43	0.46	0.49
K ₂ O		1.93	8.95	8.91	8.70	8.90	8.78	8.91	8.45	8.42	8.90	8.97
H ₂ O		4.06	3.80	4.22	4.23	4.18	4.15	4.11	4.26	4.20	4.20	4.03
F		0.12	0.70	0.00	0.00	0.06	0.16	0.27	0.02	0.21	0.03	0.34
Cl		0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Total		103.9	99.4	99.8	99.8	99.5	99.9	100.2	100.1	100.6	99.4	99.4
O=F		-0.05	-0.29	0.00	0.00	-0.03	-0.07	-0.11	-0.01	-0.09	-0.01	-0.14
O=Cl		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		103.8	99.1	99.8	99.8	99.5	99.8	100.1	100.1	100.5	99.4	99.3

Cations Based on 24 Oxygens												
Si	5.51	5.43	5.58	5.59	5.58	5.58	5.62	5.59	5.82	5.88	5.56	5.48
Ti	0.01	0.19	0.15	0.15	0.16	0.15	0.15	0.15	0.14	0.13	0.15	0.15
Al	3.69	3.15	3.08	3.09	3.10	3.06	3.06	3.07	2.93	2.88	3.13	3.21
Mg	1.24	3.99	4.17	4.15	4.12	4.11	4.11	4.17	4.01	3.99	4.15	4.15
Ca	0.16	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.01	0.00	0.00
Mn	0.14	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Fe	3.69	1.14	0.87	0.89	0.88	0.89	0.89	0.86	0.84	0.83	0.85	0.89
Na	0.02	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.13	0.14
K	0.36	1.66	1.61	1.57	1.62	1.59	1.59	1.61	1.51	1.50	1.62	1.64
<H>	3.94	3.68	15.60	15.57	15.59	15.56	15.56	15.58	15.39	15.35	15.59	15.65
<F>	0.06	0.32										
<Cl>	0.00	0.00										
total	14.8	15.7	15.6	15.6	15.6	15.6	15.6	15.6	15.4	15.3	15.6	15.7
fm	0.76	0.22	0.17	0.18	0.18	0.18	0.18	0.17	0.17	0.17	0.17	0.18
Na+K	0.37	1.78	1.74	1.70	1.75	1.71	1.71	1.73	1.64	1.62	1.74	1.77

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₁ = Rim; R₃ = Mantle; R₂ = OuterCore; R₁ = Core;.

Appendix 5c; Sample 3 Biotite

Oxide	Sample																									
	3		3		3		3		3		3		3		3		3		3		3		3			
	Position	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217	R ₃ *@217		
Point#	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233
SiO ₂	38.9	39.4	39.7	38.7	39.1	37.6	37.2	37.3	36.6	37.3	36.6	37.3	37.2	36.6	37.3	37.2	36.6	37.3	37.2	36.6	37.3	37.2	36.6	37.3	37.2	36.6
TiO ₂	1.26	1.20	1.21	1.26	1.33	0.69	0.03	0.01	0.04	0.01	0.04	0.01	0.03	0.04	0.01	0.03	0.04	0.01	0.03	0.04	0.01	0.03	0.04	0.01	0.03	0.04
Al ₂ O ₃	18.3	18.6	18.7	18.3	18.3	18.8	20.9	21.2	20.2	21.2	20.2	21.2	20.9	20.2	21.2	20.2	21.2	20.9	21.2	20.2	21.2	20.2	21.2	20.2	21.2	20.0
MgO	19.6	19.4	18.6	19.3	20.0	15.0	7.70	4.73	14.1	4.73	14.1	16.3	7.70	14.1	16.3	16.2	14.1	16.3	16.2	14.1	16.3	16.2	14.1	16.3	16.2	16.2
CaO	0.04	0.05	0.03	0.04	0.06	1.10	2.19	1.52	0.46	1.52	0.46	0.01	2.19	0.46	0.01	0.03	0.46	0.01	0.03	0.46	0.01	0.03	0.46	0.01	0.03	0.03
MnO	0.02	0.01	0.01	0.05	0.06	0.67	1.56	1.46	0.31	1.46	0.31	0.05	1.56	0.31	0.05	0.03	1.46	0.05	0.03	1.46	0.05	0.03	1.46	0.05	0.03	0.03
FeO	7.15	7.36	7.54	7.16	7.30	17.3	28.0	33.6	15.7	33.6	15.7	11.5	28.0	15.7	11.5	11.7	33.6	11.5	11.7	33.6	11.5	11.7	33.6	11.5	11.7	11.7
Na ₂ O	0.46	0.44	0.41	0.49	0.45	0.27	0.02	0.02	0.35	0.02	0.35	0.38	0.02	0.35	0.38	0.37	0.02	0.38	0.37	0.02	0.38	0.37	0.02	0.38	0.37	0.37
K ₂ O	8.74	8.67	8.84	8.82	8.65	4.58	0.04	0.05	7.52	0.05	7.52	9.42	0.05	7.52	9.42	9.40	0.05	9.42	9.40	0.05	9.42	9.40	0.05	9.42	9.40	9.40
H ₂ O	4.07	4.13	4.06	4.05	4.07	4.05	4.09	4.09	4.01	4.09	4.01	4.09	4.09	4.01	4.09	3.99	4.09	4.09	4.09	4.01	4.09	3.99	4.09	4.09	3.99	3.99
F	0.22	0.16	0.31	0.22	0.29	0.14	0.00	0.00	0.10	0.00	0.10	0.00	0.00	0.10	0.00	0.19	0.00	0.00	0.00	0.10	0.00	0.19	0.00	0.00	0.19	0.19
Cl	0.00	0.03	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.00	0.02	0.05	0.00	0.02	0.05	0.04	0.00	0.05	0.04	0.02	0.05	0.04	0.00	0.05	0.04	0.04
Total	98.8	99.5	99.5	98.4	99.5	100.2	101.8	103.9	99.4	103.9	99.4	99.2	101.8	99.4	99.2	99.0	103.9	99.4	99.2	99.4	99.2	99.0	99.4	99.2	99.0	99.0
O=F	-0.09	-0.07	-0.13	-0.09	-0.12	-0.06	0.00	0.00	-0.04	0.00	-0.04	0.00	0.00	-0.04	0.00	-0.08	0.00	-0.04	0.00	-0.04	0.00	-0.08	-0.04	0.00	-0.08	-0.08
O=Cl	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	0.00	-0.01	-0.01	0.00	-0.01	-0.01	-0.01
Total	98.7	99.4	99.4	98.3	99.4	100.1	101.8	103.9	99.4	103.9	99.4	99.2	101.8	99.4	99.2	98.9	103.9	99.4	99.2	98.9	99.2	98.9	99.4	99.2	98.9	98.9

Cations Based on 24 Oxygens

Si	5.58	5.61	5.66	5.58	5.57	5.47	5.45	5.46	5.40	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46	5.46
Ti	0.14	0.13	0.13	0.14	0.14	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	3.10	3.12	3.15	3.11	3.07	3.23	3.62	3.66	3.52	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
Mg	4.19	4.11	3.94	4.14	4.24	3.24	1.68	1.03	3.10	3.56	3.56	3.56	3.56	3.56	3.56	3.56	3.56	3.56	3.56	3.56	3.56	3.56	3.56
Ca	0.01	0.01	0.00	0.01	0.01	0.17	0.34	0.24	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Mn	0.00	0.00	0.00	0.01	0.01	0.08	0.19	0.18	0.04	0.01	0.18	0.18	0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Fe	0.86	0.88	0.90	0.86	0.87	2.10	3.44	4.12	1.94	4.12	4.12	4.12	1.94	4.12	4.12	4.12	4.12	4.12	4.12	4.12	4.12	4.12	
Na	0.13	0.12	0.11	0.14	0.12	0.08	0.01	0.00	0.10	0.00	0.00	0.00	0.10	0.00	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	
K	1.60	1.57	1.61	1.62	1.57	0.85	0.01	0.01	1.42	0.01	0.01	0.01	1.42	0.01	1.42	1.76	1.76	1.76	1.76	1.76	1.76	1.76	
Total	15.6	15.6	15.5	15.6	15.6	15.3	14.7	14.7	15.6	14.7	14.7	14.7	15.6	14.7	15.6	15.8	15.8	15.8	15.8	15.8	15.8	15.8	
fm	0.17	0.18	0.19	0.17	0.17	0.39	0.67	0.80	0.39	0.80	0.80	0.80	0.39	0.67	0.39	0.28	0.28	0.28	0.28	0.28	0.28	0.28	
Na+K	1.73	1.70	1.72	1.76	1.70	0.93	0.01	0.01	1.55	0.01	0.01	0.01	1.55	0.01	1.55	1.87	1.87	1.87	1.87	1.87	1.87	1.87	

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₃ = Rim; R₂ = Mantle; R₁ = Core.

Appendix 5c; Sample 3 Biotite

Oxide	Sample 3			Sample 3			Sample 3			Sample 3			Sample 3			Sample 3			Sample 3		
	Position	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228	R ₃ *@228
Point#	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254
Point#	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254
SiO ₂	37.2	35.7	37.6	37.7	37.8	37.8	36.8	37.5	37.2	37.2	37.7	37.7	37.6	37.2	37.7	37.6					
TiO ₂	0.00	0.02	0.02	0.00	0.04	0.00	0.05	0.01	0.01	0.01	0.00	0.05	0.01	0.01	0.01	0.14					
Al ₂ O ₃	20.8	19.9	20.2	20.4	20.5	19.9	20.2	21.2	17.0	17.0	21.2	21.2	21.2	17.0	17.4	20.8					
MgO	15.3	16.7	15.9	15.7	15.4	16.1	13.3	4.63	13.8	13.8	4.63	4.63	4.63	13.8	12.2	4.03					
CaO	0.04	0.02	0.03	0.03	0.04	0.01	0.45	1.20	0.02	0.02	1.20	1.20	1.20	0.02	0.31	5.05					
MnO	0.02	0.00	0.00	0.00	0.04	0.01	0.44	1.51	0.10	0.10	1.51	1.51	1.51	0.10	0.25	3.56					
FeO	11.0	12.5	11.3	11.4	10.9	10.5	17.4	32.9	14.9	14.9	32.9	32.9	32.9	14.9	15.0	28.7					
Na ₂ O	0.35	0.22	0.28	0.26	0.27	0.34	0.26	0.03	0.05	0.05	0.03	0.03	0.03	0.05	0.06	0.03					
K ₂ O	9.30	8.40	9.10	9.09	9.15	9.47	6.67	0.06	9.28	9.28	0.06	0.06	0.06	9.28	8.76	0.03					
H ₂ O	3.95	3.97	3.91	3.85	3.98	3.79	3.98	4.06	3.96	3.96	4.06	4.06	4.06	3.96	4.00	4.10					
F	0.24	0.09	0.36	0.50	0.23	0.62	0.17	0.02	0.13	0.13	0.02	0.02	0.02	0.13	0.01	0.00					
Cl	0.03	0.06	0.05	0.04	0.02	0.04	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.02	0.01	0.00					
Total	98.2	97.6	98.8	98.9	98.4	98.7	99.8	103.1	99.2	99.2	103.1	103.1	103.1	99.2	98.0	104.0					
O=F	-0.10	-0.04	-0.15	-0.21	-0.10	-0.26	-0.07	-0.01	-0.05	-0.05	-0.01	-0.01	-0.01	-0.05	0.00	0.00					
O=Cl	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00	-0.01	0.00	0.00					
Total	98.1	97.6	98.6	98.7	98.3	98.4	99.7	103.1	99.1	99.1	103.1	103.1	103.1	99.1	98.2	104.0					

Cations Based on 24 Oxygens

Si	5.48	5.32	5.50	5.51	5.54	5.54	5.43	5.52	5.54	5.54	5.52	5.52	5.52	5.54	5.64	5.48					
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.31	0.29	0.02					
Al	3.60	3.50	3.49	3.51	3.54	3.44	3.52	3.67	2.98	2.98	3.67	3.52	3.67	2.98	3.07	3.59					
Mg	3.36	3.71	3.47	3.42	3.36	3.53	2.92	1.02	3.05	3.05	1.02	2.92	1.02	3.05	2.72	0.88					
Ca	0.01	0.00	0.00	0.01	0.01	0.00	0.07	0.19	0.00	0.00	0.19	0.07	0.19	0.00	0.05	0.79					
Mn	0.00	0.00	0.00	0.00	0.01	0.00	0.05	0.19	0.01	0.01	0.19	0.05	0.19	0.01	0.03	0.44					
Fe	1.35	1.56	1.39	1.40	1.34	1.29	2.15	4.05	1.85	1.85	4.05	2.15	4.05	1.85	1.87	3.50					
Na	0.10	0.06	0.08	0.07	0.08	0.10	0.07	0.01	0.01	0.01	0.01	0.07	0.01	0.01	0.02	0.01					
K	1.75	1.60	1.70	1.70	1.71	1.77	1.25	0.01	1.76	1.76	0.01	1.25	0.01	1.76	1.67	0.01					
Total	15.6	15.8	15.6	15.6	15.6	15.7	15.5	14.7	15.5	15.5	14.7	15.5	14.7	15.5	15.4	14.7					
fm	0.29	0.30	0.29	0.29	0.28	0.27	0.42	0.80	0.38	0.38	0.80	0.42	0.80	0.38	0.41	0.80					
Na+K	1.84	1.66	1.78	1.77	1.78	1.87	1.33	0.02	1.78	1.78	0.02	1.33	0.02	1.78	1.69	0.01					

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₃ = Rim; R₂ = Mantle; R₁ = Core

Appendix 6a: Sample 1 Plagioclase Electron Microprobe Analyses

Appendix 6a; Sample 1 Plagioclase

Sample Position oxide	Point#	R ₁																R ₁ **Pl@35			
		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	R ₁	R ₁	R ₁	R ₁
		14	15	16	19	28	29	30	31	32	33	34	37	38							
SiO ₂	55.7	55.4	55.7	55.7	54.8	58.7	55.3	55.4	57.6	55.1	55.5	54.2	54.7								
Al ₂ O ₃	27.8	28.0	27.9	28.4	25.8	25.8	28.0	27.8	26.8	27.8	27.8	28.1	28.4								
CaO	9.83	9.83	9.80	10.4	7.40	7.40	9.96	9.97	8.39	9.8	9.93	10.5	10.6								
FeO	0.20	0.08	0.05	0.06	0.02	0.02	0.04	0.04	0.04	0.1	0.10	0.18	0.26								
Na ₂ O	5.88	5.84	5.91	5.62	7.40	7.40	5.82	5.95	6.81	5.9	5.95	5.43	5.45								
K ₂ O	0.05	0.04	0.13	0.07	0.03	0.03	0.05	0.02	0.04	0.0	0.04	0.05	0.06								
Total	99.4	99.1	99.5	99.3	99.4	99.4	99.2	99.2	99.6	98.9	99.3	98.4	99.5								

Cations Based on 8 Oxygens

Si	2.52	2.51	2.52	2.48	2.64	2.51	2.51	2.51	2.59	2.5	2.51	2.48	2.48								
Al	1.48	1.50	1.49	1.52	1.37	1.50	1.49	1.49	1.42	1.4	1.48	1.52	1.52								
Ca	0.48	0.48	0.47	0.50	0.36	0.48	0.48	0.48	0.40	0.4	0.48	0.51	0.52								
Fe	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.01	0.01								
Na	0.52	0.51	0.52	0.49	0.64	0.51	0.52	0.52	0.59	0.5	0.52	0.48	0.48								
K	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.00	0.00								
Total	5.00	5.00	5.00	5.01	5.01	5.00	5.01	5.01	5.01	5.0	5.01	5.00	5.00								

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outcore.

Appendix 6a; Sample 1 Plagioclase

Sample															
oxide	Position	R ₁ @41**	R ₁ **@42	R ₁	R ₁	R ₁ **@47	R ₁	R ₁ **@50	R ₁	R ₁ **@55	R ₁	R ₂	R ₂ **@61		
	Point#	40	43	44	45	46	48	49	53	54	56	59	60		
SiO ₂		54.5	54.9	53.8	54.6	54.6	54.1	54.0	52.0	51.8	52.3	52.7	53.0		
Al ₂ O ₃		28.5	28.1	27.9	28.3	28.1	28.5	28.5	30.1	30.1	30.0	29.1	29.2		
CaO		10.4	10.3	10.5	10.5	10.3	10.9	10.9	12.7	12.6	12.9	12.0	11.7		
FeO		0.30	0.29	0.14	0.05	0.30	0.19	0.24	0.27	0.25	0.1	0.26	0.20		
Na ₂ O		5.52	5.72	5.47	5.58	5.76	5.27	5.36	4.24	4.37	4.2	4.73	4.85		
K ₂ O		0.08	0.02	0.08	0.03	0.03	0.03	0.03	0.02	0.02	0.0	0.04	0.05		
Total		99.3	99.3	97.8	99.0	99.1	99.0	99.0	99.4	99.1	99.6	98.8	99.1		

Cations Based on 8 Oxygens

Si	2.47	2.49	2.48	2.48	2.48	2.48	2.47	2.46	2.38	2.37	2.3	2.41	2.42		
Al	1.53	1.50	1.52	1.52	1.52	1.51	1.53	1.53	1.62	1.62	1.6	1.57	1.57		
Ca	0.51	0.50	0.52	0.51	0.50	0.50	0.53	0.53	0.62	0.62	0.6	0.59	0.57		
Fe	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.0	0.01	0.01		
Na	0.49	0.50	0.49	0.49	0.49	0.51	0.47	0.47	0.38	0.39	0.3	0.42	0.43		
K	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0	0.00	0.00		
Total	5.01	5.01	5.01	5.01	5.01	5.02	5.00	5.01	5.00	5.01	5.0	5.01	5.01		

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outcore;

Appendix 6b: Sample 2 Plagioclase Electron Microprobe Analyses

Appendix 6b; Sample 2 Plagioclase

oxide	Sample Position Point#	2		2		2		2		2		2		2		2	
		R ₂ **@19	R ₂	R ₂ **@24	R ₂ **@24	R ₂ **@24	R ₂ **@24	R ₂ **@27	R ₂	R ₂ **@32	R ₂ **@32	R ₃ **@56	R ₃	R ₃	R ₃	R ₃	
		20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
SiO ₂		57.4	57.5	57.5	0.10	58.1	57.8	58.0	55.8	55.3							
Al ₂ O ₃		26.5	26.4	26.4	0.00	26.4	26.3	26.3	27.7	27.6							
CaO		8.33	8.33	8.26	54.3	8.00	7.98	8.09	9.70	9.68							
FeO		0.16	0.04	0.14	0.30	0.15	0.01	0.17	0.15	0.18							
Na ₂ O		6.80	6.67	6.75	0.09	6.90	6.94	6.98	6.02	6.14							
K ₂ O		0.09	0.11	0.10	0.01	0.05	0.05	0.04	0.04	0.03							
Total		99.3	99.0	99.2	54.8	99.5	99.1	99.6	99.3	98.9							
Cations Based on 8 Oxygens																	
Si		2.59	2.60	2.59	0.01	2.61	2.61	2.61	2.52	2.52							
Al		1.41	1.41	1.41	0.00	1.40	1.40	1.39	1.47	1.48							
Ca		0.40	0.40	0.40	7.93	0.39	0.39	0.39	0.47	0.47							
Fe		0.01	0.00	0.01	0.04	0.01	0.00	0.01	0.01	0.01							
Na		0.60	0.58	0.59	0.02	0.60	0.61	0.61	0.53	0.54							
K		0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00							
Total		5.01	5.00	5.00	8.00	5.00	5.00	5.00	5.00	5.02							

Cations Based on 8 Oxygens

Si	2.59	2.60	2.59	2.59	2.59	2.59	2.59	2.59	2.61	2.61	2.61	2.61	2.52	2.52			
Al	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.40	1.40	1.39	1.39	1.47	1.48			
Ca	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.47	0.47			
Fe	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01			
Na	0.60	0.58	0.58	0.59	0.59	0.59	0.59	0.59	0.60	0.61	0.61	0.61	0.53	0.54			
K	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00			
Total	5.01	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.02			

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outcore.

Appendix 6b; Sample 2 Plagioclase

Sample		2		2		2		2		2		2		2		2		2	
Position	R ₄	R ₁ **@119	R ₄ **@119	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄	R ₄
Oxide	Point#	112	113	114	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135
SiO ₂		59.2	59.5	59.7	57.1	59.2	58.9	58.7	56.5	56.7	56.8	56.3							
Al ₂ O ₃		25.3	25.6	25.9	25.0	25.4	25.4	25.6	27.2	27.3	27.3	27.4							
CaO		7.37	7.25	7.21	7.30	7.41	7.32	7.59	9.51	9.51	9.39	9.56							
FeO		0.19	0.24	0.50	1.61	0.27	0.24	0.04	0.22	0.22	0.40	0.25							
Na ₂ O		7.44	7.39	7.34	6.72	7.45	7.58	7.26	6.18	6.17	6.07	6.13							
K ₂ O		0.13	0.13	0.14	0.09	0.09	0.12	0.12	0.23	0.18	0.22	0.18							
Total		99.6	100.1	100.8	97.8	99.9	99.6	99.3	99.9	100.1	100.2	99.9							
Cations Based on 8 Oxygens																			
Si		2.65	2.65	2.64	2.62	2.65	2.65	2.64	2.54	2.55	2.55	2.54							
Al		1.34	1.34	1.35	1.35	1.34	1.34	1.36	1.44	1.45	1.44	1.46							
Ca		0.35	0.35	0.34	0.36	0.36	0.35	0.37	0.46	0.46	0.45	0.46							
Fe		0.01	0.01	0.02	0.06	0.01	0.01	0.00	0.01	0.01	0.02	0.01							
Na		0.65	0.64	0.63	0.60	0.65	0.66	0.63	0.54	0.54	0.53	0.54							
K		0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01							
Total		5.01	5.00	5.00	5.00	5.01	5.02	5.00	5.01	5.01	5.00	5.01							

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outercore.

Appendix 6c: Sample 3 Plagioclase Electron Microprobe Analyses

Appendix 6c; Sample 3 Plagioclase

Sample Position Oxide	3			3			3			3			3			3			3			3		
	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i	R _i
Point#	61	62	63	64	65	69	70	71	72	73	77	78												
SiO ₂	60.0	59.6	60.2	60.0	43.2	59.2	59.7	59.6	60.2	59.4	60.0	59.7												
Al ₂ O ₃	25.0	25.1	24.8	24.9	22.0	25.3	25.1	25.1	24.8	24.9	25.4	24.9												
CaO	6.69	6.63	6.32	6.51	4.35	6.83	6.54	6.77	6.54	6.58	6.71	6.62												
FeO	0.15	0.13	0.37	0.44	13.70	0.36	0.32	0.05	0.24	0.35	0.39	0.18												
Na ₂ O	7.65	7.62	7.82	7.79	2.90	7.97	7.75	7.67	7.69	7.89	7.58	7.91												
K ₂ O	0.30	0.33	0.32	0.37	0.17	0.24	0.27	0.27	0.36	0.31	0.29	0.26												
Total	99.7	99.4	99.9	100.0	86.3	99.9	99.7	99.5	99.9	99.4	100.4	99.5												
Cations Based on 8 Oxygens																								
Si	2.68	2.67	2.69	2.68	2.39	2.65	2.67	2.67	2.69	2.67	2.67	2.68												
Al	1.32	1.33	1.31	1.31	1.44	1.33	1.32	1.33	1.31	1.32	1.33	1.32												
Ca	0.32	0.32	0.30	0.31	0.26	0.33	0.31	0.33	0.31	0.32	0.32	0.32												
Fe	0.01	0.01	0.01	0.02	0.64	0.01	0.01	0.00	0.01	0.01	0.02	0.01												
Na	0.66	0.66	0.68	0.68	0.31	0.69	0.67	0.67	0.67	0.69	0.65	0.69												
K	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02												
Total	5.00	5.01	5.01	5.01	5.05	5.03	5.01	5.01	5.00	5.03	5.00	5.02												

*Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outercore

Appendix 6c; Sample 3 Plagioclase

Sample Position oxide	3			3			3			3			3			3			3			3		
	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂	R ₂ **@84	R ₃ @88	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112	R ₃ **@112
Point#	80	81	82	83	87	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123
SiO ₂	59.7	59.4	60.0	59.6	59.5	54.7	54.6	54.5	54.6	54.3														
Al ₂ O ₃	25.0	25.1	24.9	25.3	25.2	28.1	28.0	27.9	28.0	28.0														
CaO	6.62	6.65	6.55	6.79	6.85	10.8	10.9	11.0	10.8	10.9														
FeO	0.02	0.04	0.39	0.55	0.25	0.19	0.29	0.27	0.29	0.29														
Na ₂ O	7.68	7.55	7.61	7.56	7.87	5.49	5.42	5.46	5.41	5.42														
K ₂ O	0.39	0.42	0.32	0.28	0.20	0.16	0.15	0.14	0.15	0.14														
Total	99.3	99.2	99.8	100.0	99.9	99.5	99.4	99.3	99.3	99.2														

Cations Based on 8 Oxygens																								
Si	2.68	2.67	2.68	2.66	2.66	2.48	2.48	2.48	2.48	2.47														
Al	1.32	1.33	1.31	1.33	1.33	1.50	1.50	1.50	1.50	1.51														
Ca	0.32	0.32	0.31	0.33	0.33	0.53	0.53	0.53	0.53	0.53														
Fe	0.00	0.00	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01														
Na	0.67	0.66	0.66	0.66	0.68	0.48	0.48	0.48	0.48	0.48														
K	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01														
Total	5.01	5.00	5.00	5.01	5.02	5.01	5.01	5.01	5.01	5.02														

*Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outercore.

Appendix 6c: Sample 3 Plagioclase

Oxide	Sample 3			Sample 3			Sample 3			Sample 3			Sample 3			Sample 3			Sample 3			Sample 3		
	Position	R ₁ **@167	R ₁ **@167	R ₁ **@167	R ₁ **@167	R ₁ **@167	R ₃ **@222	R ₃ **@222	R ₃ **@222	R ₃ **@222	R ₃ **@222	R ₃ **@222	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262
Point#	160	161	162	163	167	167	219	220	221	221	221	221	253	254	255	256	256	256	256	256	256	257	257	257
SiO ₂	56.8	57.0	58.7	53.2	59.4	59.4	58.9	58.9	38.3	38.3	38.3	38.3	56.5	56.4	56.5	56.4	56.4	56.4	56.4	56.4	56.4	56.5	56.5	56.5
Al ₂ O ₃	27.3	27.0	27.3	23.8	25.5	25.5	25.8	25.8	21.1	21.1	21.1	21.1	27.5	27.7	27.6	27.5	27.5	27.5	27.5	27.5	27.5	27.7	27.7	27.7
CaO	9.43	9.36	8.58	6.62	7.77	7.77	7.58	7.58	2.18	2.18	2.18	2.18	10.0	10.1	10.0	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
FeO	0.30	0.33	0.53	1.70	0.23	0.23	0.81	0.81	26.58	26.58	26.58	26.58	0.19	0.29	0.28	0.31	0.31	0.31	0.31	0.31	0.31	0.34	0.34	0.34
Na ₂ O	6.18	6.31	6.23	4.28	7.25	7.25	7.28	7.28	0.02	0.02	0.02	0.02	5.87	5.97	5.90	5.90	5.90	5.90	5.90	5.90	5.90	5.90	5.90	5.90
K ₂ O	0.19	0.21	0.25	1.59	0.04	0.04	0.03	0.03	0.00	0.00	0.00	0.00	0.15	0.14	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.15	0.15	0.15
Total	100.1	100.2	101.6	91.1	100.2	100.2	100.4	100.4	88.1	88.1	88.1	100.3	100.3	100.5	100.5	100.4	100.4	100.4	100.4	100.4	100.4	100.7	100.7	100.7

Cations Based on 8 Oxygens																								
Si	2.55	2.56	2.59	2.63	2.65	2.65	2.63	2.63	2.21	2.21	2.21	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53	2.53
Al	1.44	1.43	1.42	1.38	1.34	1.34	1.36	1.36	1.44	1.44	1.44	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46	1.46
Ca	0.45	0.45	0.41	0.35	0.37	0.37	0.36	0.36	0.13	0.13	0.13	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.49	0.49	0.49
Fe	0.01	0.01	0.02	0.07	0.01	0.01	0.03	0.03	1.29	1.29	1.29	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Na	0.54	0.55	0.53	0.41	0.63	0.63	0.63	0.63	0.00	0.00	0.00	0.51	0.51	0.52	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51
K	0.01	0.01	0.01	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Total	5.00	5.01	4.98	4.94	5.00	5.00	5.01	5.01	5.07	5.07	5.07	5.00	5.00	5.01	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00

*Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outercore.

Appendix 6c; Sample 3 Plagioclase

Oxide	Sample		R ₂		R ₂		R ₂		R ₂		R ₂		R ₂		R ₂		R ₂	
	Position	R ₂	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262	R ₂ **@262
	Point#	258	259	264	264	265	265	266	266	267	267	268	268	274	274	275	275	276
SiO ₂		56.2	43.9	51.1	51.1	51.4	51.4	51.5	51.5	51.5	51.5	41.5	41.5	53.6	53.6	53.5	53.5	52.7
Al ₂ O ₃		27.7	25.3	30.8	30.8	30.8	30.8	30.7	30.7	30.7	30.7	23.1	23.1	29.3	29.3	29.4	29.4	29.1
CaO		10.2	5.63	13.9	13.9	13.8	13.8	13.8	13.8	13.8	13.8	8.90	8.90	12.0	12.0	12.0	12.0	10.3
FeO		0.37	10.30	0.34	0.34	0.37	0.37	0.33	0.33	0.26	0.26	14.90	14.90	0.44	0.44	0.47	0.47	1.12
Na ₂ O		5.69	1.91	3.83	3.83	3.80	3.80	3.81	3.81	3.84	3.84	1.51	1.51	4.71	4.71	4.80	4.80	3.75
K ₂ O		0.17	0.09	0.06	0.06	0.03	0.03	0.05	0.05	0.05	0.05	0.02	0.02	0.20	0.20	0.22	0.22	0.18
Total		100.3	87.2	100.1	100.1	100.2	100.2	100.2	100.2	100.3	100.3	89.9	89.9	100.3	100.3	100.4	100.4	97.1
Cations Based on 8 Oxygens																		
Si		2.52	2.35	2.33	2.33	2.34	2.34	2.34	2.34	2.34	2.34	2.25	2.25	2.42	2.42	2.42	2.42	2.44
Al		1.47	1.60	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.65	1.48	1.48	1.56	1.56	1.57	1.57	1.59
Ca		0.49	0.32	0.68	0.68	0.67	0.67	0.67	0.67	0.67	0.67	0.52	0.52	0.58	0.58	0.58	0.58	0.51
Fe		0.01	0.46	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.68	0.68	0.02	0.02	0.02	0.02	0.04
Na		0.50	0.20	0.34	0.34	0.33	0.33	0.34	0.34	0.34	0.34	0.16	0.16	0.41	0.41	0.42	0.42	0.34
K		0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	-0.01
Total		5.00	4.95	5.02	5.02	5.01	5.01	5.01	5.01	5.01	5.01	5.09	5.09	5.01	5.01	5.02	5.02	4.93

*Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₄ = Rim; R₃ = Mantle; R₂ = OuterCore; R₁ = Core; (o-c) = Outcore

Appendix 7b: Sample 2 Ilmenite Electron Microprobe Analyses

Appendix 7b; Sample 2 Ilmenite

Appendix 10: Sample 2: Anorthite																					
Sample Position	R _a	2	R _a **@143	2	R _a	2	R _a	2	R _a **@152	2	R _a	2	R _a	2	R _a	2	R _a	2	R _a	2	R _a **@160
Oxide	Point#	137	138	139	140	144	145	146	147	148	153	154									
SiO ₂		0.02	0.00	0.02	0.04	0.02	0.01	0.04	0.05	0.15	0.02	0.01									
TiO ₂		52.8	52.9	52.7	52.5	53.0	52.7	52.5	52.5	52.4	52.6	53.0									
Al ₂ O ₃		0.00	0.00	0.01	0.00	0.01	0.02	0.00	0.01	0.10	0.00	0.01									
Cr ₂ O ₃		0.00	0.01	0.01	0.02	0.02	0.03	0.01	0.00	0.03	0.00	0.03									
MgO		1.91	1.91	1.93	1.94	1.91	1.89	1.93	1.90	1.92	0.89	0.89									
CaO		0.00	0.02	0.04	0.05	0.01	0.02	0.01	0.04	0.08	0.02	0.03									
MnO		0.20	0.19	0.20	0.20	0.19	0.23	0.18	0.21	0.21	0.41	0.44									
FeO		43.7	44.0	43.7	43.8	44.1	44.0	43.7	43.5	43.6	45.1	45.0									
Na ₂ O		0.00	0.00	0.02	0.00	0.02	0.02	0.02	0.01	0.00	0.03	0.00									
Total		98.7	99.0	98.6	98.6	99.3	98.9	98.4	98.3	98.6	99.1	99.4									
Fm		0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.97	0.97									
Cations Based on 3 Oxygens																					
Si		0.001	0.000	0.000	0.001	0.001	0.000	0.001	0.001	0.004	0.000	0.000									
Ti		1.001	1.000	0.999	0.996	0.999	0.997	0.998	0.999	0.994	1.001	1.003									
Al		0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.003	0.000	0.000									
Cr		0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.001									
Mg		0.072	0.072	0.073	0.073	0.071	0.071	0.073	0.072	0.072	0.034	0.033									
Ca		0.000	0.001	0.001	0.001	0.000	0.001	0.000	0.001	0.002	0.001	0.001									
Mn		0.004	0.004	0.004	0.004	0.004	0.005	0.004	0.004	0.005	0.009	0.009									
Fe		0.922	0.924	0.921	0.924	0.984	0.924	0.923	0.921	0.920	0.954	0.948									
Na		0.000	0.000	0.001	0.000	0.001	0.001	0.001	0.000	0.000	0.001	0.000									
Total		1.999	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	1.999	1.996									
*Used for thermometry; ** Used for barometry; All Fe reported as Fe ²⁺ ; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outcore.																					

*Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outercore.

Appendix 7b; Sample 2 Ilmenite

Oxide	Sample		2		2		2		2		2		2		2		2		2	
	Position	Point#	R ₃ **@160	R ₃ **@160	R ₃	R ₃	R ₃ **@164	R ₂	R ₂	R ₂	R ₂	R ₂	R ₁ **@170	R ₁	R ₁	R ₁	R ₁	R ₁	R ₁ **@173	R ₁
			155	156	157	158	163	165	166	167	168	169	172							
SiO ₂			0.02	0.03	0.04	0.05	0.01	0.02	0.02	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.02	0.02
TiO ₂			53.0	52.7	52.6	52.8	52.7	52.9	52.7	52.7	52.4	43.9	52.6	52.4	43.9	43.9	52.6	52.4	52.6	52.6
Al ₂ O ₃			0.00	0.01	0.01	0.00	0.00	0.01	0.02	0.02	0.01	4.35	0.03	0.01	4.35	4.35	0.03	0.01	0.03	0.03
Cr ₂ O ₃			0.01	0.00	0.00	0.00	0.00	0.06	0.04	0.04	0.00	0.00	0.04	0.00	0.00	0.00	0.04	0.00	0.04	0.04
MgO			0.88	0.86	0.86	0.87	0.90	1.53	1.55	1.55	1.50	1.86	1.54	1.50	1.86	1.86	1.54	1.50	1.54	1.54
CaO			0.02	0.03	0.05	0.07	0.06	0.01	0.11	0.18	0.32	1.34	0.09	0.32	1.34	1.34	0.09	0.32	0.09	0.09
MnO			0.55	0.49	0.56	0.53	0.50	1.49	1.52	1.48	1.49	1.89	1.48	1.49	1.89	1.89	1.48	1.49	1.48	1.48
FeO			44.7	45.0	44.7	44.6	44.7	43.4	43.5	43.0	43.1	38.8	43.2	43.1	38.8	38.8	43.2	43.1	43.2	43.2
Na ₂ O			0.00	0.00	0.00	0.01	0.01	0.03	0.00	0.04	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.02	0.02
Total			99.1	99.1	98.8	98.9	98.9	99.4	99.4	99.0	98.9	98.5	99.0	98.9	98.5	98.5	99.0	98.9	99.0	99.0
Fm			0.97	0.97	0.97	0.97	0.97	0.94	0.94	0.94	0.94	0.92	0.94	0.94	0.92	0.92	0.94	0.94	0.94	0.94

Cations Based on 3 Oxygens																				
Si	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.154	0.001	0.001	0.001	0.154	0.001	0.001	0.001	0.001
Ti	1.005	1.002	1.002	1.004	1.002	1.004	1.003	0.998	0.994	0.996	0.994	0.794	0.996	0.994	0.994	0.794	0.996	0.994	0.996	0.996
Al	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.123	0.001	0.000	0.000	0.123	0.001	0.000	0.001	0.001
Cr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.001	0.001
Mg	0.033	0.032	0.032	0.032	0.032	0.033	0.034	0.057	0.058	0.058	0.056	0.067	0.058	0.056	0.067	0.067	0.058	0.056	0.058	0.058
Ca	0.000	0.001	0.001	0.002	0.001	0.002	0.002	0.000	0.003	0.005	0.009	0.034	0.002	0.009	0.034	0.034	0.002	0.009	0.002	0.002
Mn	0.012	0.011	0.012	0.011	0.012	0.011	0.011	0.032	0.032	0.031	0.032	0.039	0.031	0.032	0.039	0.039	0.032	0.032	0.032	0.032
Fe	0.943	0.951	0.947	0.943	0.947	0.943	0.946	0.910	0.911	0.905	0.908	0.780	0.905	0.908	0.780	0.780	0.909	0.908	0.909	0.909
Na	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.002	0.000	0.000	0.002	0.000	0.000	0.000	0.001	0.000	0.001	0.001
Total	1.994	1.997	1.996	1.995	1.996	1.995	1.997	2.000	2.000	2.000	2.000	1.991	2.000	2.000	1.991	1.991	2.000	2.000	2.000	2.000

*Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R4 = Rim; R3 = Mantle; R2 = OuterCore; R1 = Core; (o-c) = Outercore.

Appendix 7c: Sample 3 Ilmenite Electron Microprobe Analyses

Appendix 7c; Sample 3 Ilmenite

Oxide	Sample 3		3		3		3		3		3		3		3	
	Position	R ₁ **@34	R ₁ **@34	R ₁ **@34	R ₁ **@34	R ₁ **@34	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c	R ₂ **@190b,c
Point#	36	37	38	39f	39g	39h	39i	39j	39k	39l	39m	39n	39o	39p	39q	39r
SiO ₂	0.08	0.00	0.03	0.08	0.02	0.03	0.01	0.03	0.02	0.03	0.01	0.03	0.02	0.03	0.01	0.03
TiO ₂	52.1	53.0	52.4	52.9	53.3	53.2	53.4	53.2	53.3	53.2	53.4	53.2	53.3	53.2	53.4	53.2
Al ₂ O ₃	0.04	0.02	0.02	0.07	0.02	0.02	0.00	0.02	0.02	0.02	0.00	0.02	0.02	0.02	0.00	0.02
Cr ₂ O ₃	0.00	0.00	0.03	0.04	0.00	0.00	0.03	0.04	0.00	0.00	0.03	0.04	0.00	0.00	0.03	0.04
MgO	1.00	0.97	0.97	1.92	1.98	1.88	1.91	1.92	1.98	1.88	1.91	1.92	1.98	1.88	1.91	1.92
CaO	0.06	0.01	0.04	0.07	0.03	0.02	0.02	0.07	0.03	0.02	0.02	0.07	0.03	0.02	0.02	0.07
MnO	0.75	0.68	0.67	0.66	0.49	0.54	0.54	0.66	0.49	0.54	0.54	0.66	0.49	0.54	0.54	0.66
FeO	44.8	44.8	44.9	44.2	43.7	44.3	43.9	44.2	43.7	44.3	43.9	44.2	43.7	44.3	43.9	44.2
Na ₂ O	0.01	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.00	0.00
Total	98.8	99.5	99.1	99.9	99.5	100.0	99.8	99.9	99.5	100.0	99.8	99.9	99.5	100.0	99.8	99.8
Fm	0.96	0.96	0.96	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Cations Based on 3 Oxygens																
Si	0.002	0.000	0.001	0.002	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.000
Ti	0.993	1.003	0.997	0.992	1.000	0.996	1.000	0.992	1.000	0.996	1.000	0.992	1.000	0.996	1.000	0.996
Al	0.001	0.001	0.001	0.002	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.000
Cr	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.001
Mg	0.038	0.037	0.037	0.071	0.074	0.070	0.071	0.071	0.074	0.070	0.071	0.071	0.074	0.070	0.071	0.071
Ca	0.002	0.000	0.001	0.002	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.002	0.001	0.001	0.000	0.001
Mn	0.016	0.015	0.014	0.014	0.010	0.011	0.011	0.014	0.010	0.011	0.011	0.014	0.010	0.011	0.011	0.011
Fe	0.948	0.942	0.950	0.922	0.913	0.922	0.915	0.922	0.913	0.922	0.915	0.922	0.913	0.922	0.915	0.915
Na	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.000	0.000
Total	2.000	1.997	2.000	2.005	1.999	2.003	1.999	2.005	1.999	2.003	1.999	2.005	1.999	2.003	1.999	1.999

*Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R3 = Rim; R4 = Core; R2 = OuterCore; R1 = Core.

Appendix 8a: Sample 3 K-feldspar Electron Microprobe Analyses

Appendix 8b: Sample 2 Muscovite Electron Microprobe Analyses

Appendix 9: Mineral Abbreviations

Appendix 8b: Sample 2 Muscovite

Oxide	Sample Position Point#	2		2		2		2		2		2	
		R ₄	183	R ₄	184	R ₄	185	@PI189	186	R ₄	187	R ₄ @PI191	188
SiO ₂		46.7		46.4		45.7		45.9		60.4		61.7	
TiO ₂		0.39		0.37		0.12		0.87		0.04		0.00	
Al ₂ O ₃		34.3		33.2		34.3		33.6		23.9		24.0	
MgO		1.37		1.39		1.23		1.41		0.59		0.00	
CaO		0.00		0.10		0.00		0.01		5.03		5.49	
MnO		0.00		0.02		0.00		0.00		0.02		0.02	
FeO		1.10		1.05		1.01		1.06		0.63		0.04	
Na ₂ O		0.58		0.95		0.85		0.81		8.05		8.66	
K ₂ O		8.98		9.92		10.1		10.1		0.54		0.06	
H ₂ O		4.46		4.41		4.33		4.43		4.84		4.89	
F		0.00		0.02		0.19		0.00		0.01		0.05	
Cl		0.01		0.00		0.00		0.01		0.01		0.00	
Total		97.8		97.8		97.9		98.3		104.0		104.9	
O=F		0.00		-0.01		-0.08		0.00		-0.01		-0.02	
O=Cl		0.00		0.00		0.00		0.00		0.00		0.00	
Total		97.8		97.7		97.8		98.3		104.0		104.9	

Cations Based on 24 Oxygens

Si	6.27	6.29	6.20	6.20	6.20	7.47	7.54
Ti	0.04	0.04	0.01	0.01	0.09	0.00	0.00
Al	5.43	5.30	5.49	5.49	5.35	3.47	3.45
Mg	0.27	0.28	0.25	0.25	0.28	0.11	0.00
Ca	0.00	0.01	0.00	0.00	0.00	0.67	0.72
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.12	0.12	0.11	0.11	0.12	0.06	0.00
Na	0.15	0.25	0.22	0.22	0.21	1.93	2.05
K	1.54	1.72	1.75	1.75	1.75	0.08	0.01
<H>	13.8	14.0	14.0	14.0	14.0	13.8	13.8
<F>	4.00	3.99	3.92	3.92	4.00	3.99	3.98
<Cl>	0.00	0.01	0.08	0.08	0.00	0.01	0.02
total	0.00	0.00	0.00	0.00	0.00	0.00	0.00
fm	0.31	0.30	0.32	0.32	0.30	0.38	1.00
Na+K	1.69	1.97	1.97	1.97	1.96	2.01	2.06

* Used for thermometry; ** Used for barometry; All Fe reported as Fe²⁺; R₄ = Rim; R₃ = Mantle; R₂ = OuterCore; R₁ = Core.

Mineral Abbreviations

AlSi: Aluminum Silicate.

An: Anorthite

And: Andalusite.

Bt: Biotite

Gt: Garnet.

Ilm: Ilmenite.

K-spar: K-feldspar.

Ky: Kyanite.

Mu: Muscovite.

Pl, Plag: Plagioclase.

Qtz: Quartz.

Rt: Rutile.

Sill, Sil: Sillimanite.

St: Staurolite.

VITA

Milo Cameron was born in Yonkers, New York. His early childhood and adolescence years were spent in the shoreline towns of New London and Clinton, Connecticut. Family camping trips to the Adirondack Mountains fueled his curiosity about rocks and minerals. After graduating from high school he volunteered to help a Missionary in Guatemala. This started a period of travel throughout North and South America and also rekindled an interest in geologic processes. Milo's involvement in tennis, music, and poetry kept him busy for a period of 10 years. During that time period he taught tennis at the renowned Nick Bollettieri tennis academy. After taking an introductory course in geology at the University of Alabama in Huntsville, he knew that he wanted to study geology more intensely and eventually was accepted into the graduate program in geology at The University of Tennessee in Knoxville. It was during this period that two goals were achieved: A degree in geology and the production of his first CD...

