EVOLUTION OF THE PHLOGOPITE-CHROME DIOPSIDE-SPINEL POOLS IN THE ULTRAMAFIC NODULES OF PIPE 200, NORTHERN LESOTHO

Eva Schandl

Submitted in partial fulfillment of the requirements for the degree of Bachelor of Science (Honours), Department of Geology, Dalhousie University, Halifax, N.S.

March 1980

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

DALHOUSIE UNIVERSITY, DEPARTMENT OF GEOLOGY

B.Sc. HONOURS THESIS

Author: Eva SCHANDL

Title: EVOLUTION OF THE PHLOGOPITE-CHROME DIOPSIDE-SPINEL POOLS IN THE ULTRAMAFIC NODULES OF PIPE 200, NORTHERN LESOTHO

Signature of author

Date: May 1980

Distribution License

DalSpace requires agreement to this non-exclusive distribution license before your item can appear on DalSpace.

NON-EXCLUSIVE DISTRIBUTION LICENSE

You (the author(s) or copyright owner) grant to Dalhousie University the non-exclusive right to reproduce and distribute your submission worldwide in any medium.

You agree that Dalhousie University may, without changing the content, reformat the submission for the purpose of preservation.

You also agree that Dalhousie University may keep more than one copy of this submission for purposes of security, back-up and preservation.

You agree that the submission is your original work, and that you have the right to grant the rights contained in this license. You also agree that your submission does not, to the best of your knowledge, infringe upon anyone's copyright.

If the submission contains material for which you do not hold copyright, you agree that you have obtained the unrestricted permission of the copyright owner to grant Dalhousie University the rights required by this license, and that such third-party owned material is clearly identified and acknowledged within the text or content of the submission.

If the submission is based upon work that has been sponsored or supported by an agency or organization other than Dalhousie University, you assert that you have fulfilled any right of review or other obligations required by such contract or agreement.

Dalhousie University will clearly identify your name(s) as the author(s) or owner(s) of the submission, and will not make any alteration to the content of the files that you have submitted.

If you have questions regarding this license please contact the repository manager at dalspace@dal.ca.

Grant the distribution license by signing and dating below.

______________________________ ______________________________

Name of signatory Date

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Peridotites are ultramafic igneous plutonic rocks consisting of predominantly ferromagnesian minerals. Their mineralogy reflects their stability field at different pressures and temperatures.

olivine-2 pyroxenes-garnet: high pressure assemblage
olivine-2 pyroxenes-spinel: lower pressure assemblage
olivine-pyroxenes-plag: lowest pressure assemblage

Peridotites are generally of mantle origin.

The sampling of the upper mantle by kimberlite permits the study of mantle rocks; their depth of origin, mineral assemblages, and the processes responsible for their formation. Partial melting of peridotite produces a basaltic melt and leaves behind a depleted peridotite. Depending upon subsequent events, these peridotites may be metasomatized and altered prior to incorporation into the kimberlite (primary metasomatism) and during transportation in the kimberlite (secondary metasomatism). If the depleted peridotites are metasomatised, however, it is difficult to recognize and make distinction between the new properties acquired during primary and secondary metasomatism. Two of the criteria that have been used to separate the primary and secondary events are, (a) phlogopite chemistry, (b) textural evidence

such as grain deformation, kelyphytization and polygonization. The garnet lherzolites of the kimberlites from Pipe 200 Lesotho have been extensively metasomatised. Although both primary and secondary metasomatising events are recognised in the "subset nodules" of Pipe 200, there are some rocks that lack evidence for primary metasomatism in the other PTH nodules.

The subset nodules differ from the rest of the garnet lherzolites by the presence of 'pools'. The term 'pool' refers to a mineral assemblage consisting of phlogopite + chrome diopside + spinel. Pool shapes are roughly spherical, with a mosaic texture, and the presence of phlogopites suggests metasomatic origin. The pools are thought to be the result of a combination of processes:

(a) Solid-state metamorphic reaction $Mg_2SiO_4 + CaMg_2Al_2Si_3O_{12} \rightarrow CaMgSi_2O_6 + 2MgSiO_3 + MgAl_2O_4$

(b) metasomatising fluid promoted the development of phlogopite-rich pools with the chrome diopsides and spinels.

The presence of the pools is a strong indication of metamorphism followed by metasomatism. Phlogopites in the pools are strained, suggesting crystallization prior to incorporation into the kimberlite. The lack of pools in some nodules suggests that metasomating events were local phenomena to some degree, and did not affect all the nodules to the same extent.

CHAPTER I: INTRODUCTION

INTRODUCTION

Pipe 200 is situated in northern Lesotho, South Africa. It is about 8 km west of the Kao kimberlite area, close to the Letele Pass (Carswell *et al.*, 1979). A large number of ultramafic inclusions were found in this kimberlite. Extensive petrological and geochemical work has been completed on the Pipe 200 peridotite nodules by Carswell *et al.* (1979); and their paper titled "The Petrology and Geochemistry of Ultramafic Nodules from Pipe 200, Northern Lesotho" serves as a basis for the present thesis. The peridotite nodules of Pipe 200 are harzburgites, lherzolites and four-phase garnet lherzolites. Their mineral assemblages consists of predominantly forsteritic olivine, enstatitic orthopyroxene, chrome diopside and chrome pyrope garnet. Other genetically important minor minerals present are phlogopites and spinels. The nodules have high Mg (Mg + Fe) ratio, high Cr_2O_3 and low Na_2O content characteristic features of mantle rocks that have suffered partial melting (Carswell *et al.*, 1979). Serpentinization is apparent, and the occasional kink-bands, elongation of grains coupled with undulose extinction are the result of deformation. The "subset nodules" are a suite of six nodules from the PTH rocks. They were selected for the topic of this thesis since they contain small 'pools' of mineral aggregates that differ from the rest of the rocks. Their difference is manifest in the presence of phlogopites, the varied and unusual shapes of spinel, and the spongy, serrated rims of chrome diopsides. The most significant difference exists between the rest of the nodules and the rocks PTH 108, 516 and 204 which contain well-crystallized 'pools'. The 'pools' are spherical mineral aggregates within the nodules, occupying areas of about 3 x 5 mm. They consist of the mineral assemblage phlogopite, chrome diopside, minor spinel. In general, crystal sizes in the pools are smaller than the average grain sizes in the rock, and they constitute only a small percentage of the overall composition.

The origin of these pools is not known. It is hoped, that by closely examining the chemistry, mineralogy, and most important of all, the textural features of all the pools, some light will be shed on the place and their mode of formation.

Techniques used for analysis were:

1. Electron microprobe: (i) coexisting phases for T-P estimates
   (ii) mass balance calculations
2. Classification by mineral chemistry of garnets, orthopyroxenes, clinopyroxenes, phlogopites

3. Petrography/texture

The General Geology of Pipe 200

Pipe 200 is comprised of three kimberlite types: aphanitic, agglomeratic and porphyritic (Fig. 1). The three types often grade into one another, suggesting different ages of emplacement for each type (Kresten and Dempster, 1973). The first intrusion was believed to be the aphanitic kimberlite, followed by the agglomeratic, then finally the porphyritic types. The agglomeratic kimberlite was explosively emplaced as it broke through the aphanitic kimberlite dykes. Presently it occupies a space that was once filled with the aphanitic kimberlite. The last intrusion, the porphyritic type, was the result of slow emplacement, and slow ascent of the solid or semi-solid mass.

Inclusions in the kimberlite consist of crustal inclusions of sedimentary rocks (sandstone, siltstone), basement rocks (garnet gneisses and amphibolites), and deep crustal rocks (granulites, eclogites). The ultramafic rocks found in the kimberlites are garnet lherzolites, lherzolites and dunites (in order of decreasing abundances).

Kimberlitic inclusions are kimberlite types other than the host. The agglomerates contain the highest percentage

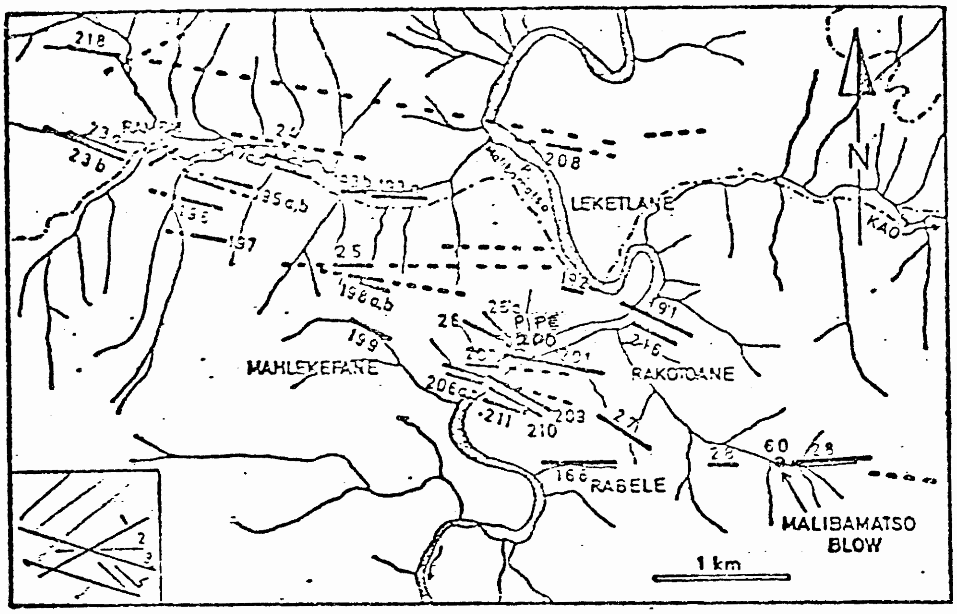


Figure 45 Sketch map of the Malibamatso dyke swarm area. Solid black lines are kimberlites (with number), dashed lines are prominent joint zones. ~~Inset refers to mechanism of intrusion discussed in the text.~~

F I G . 1 . (Kresten and Dempster, 1973)

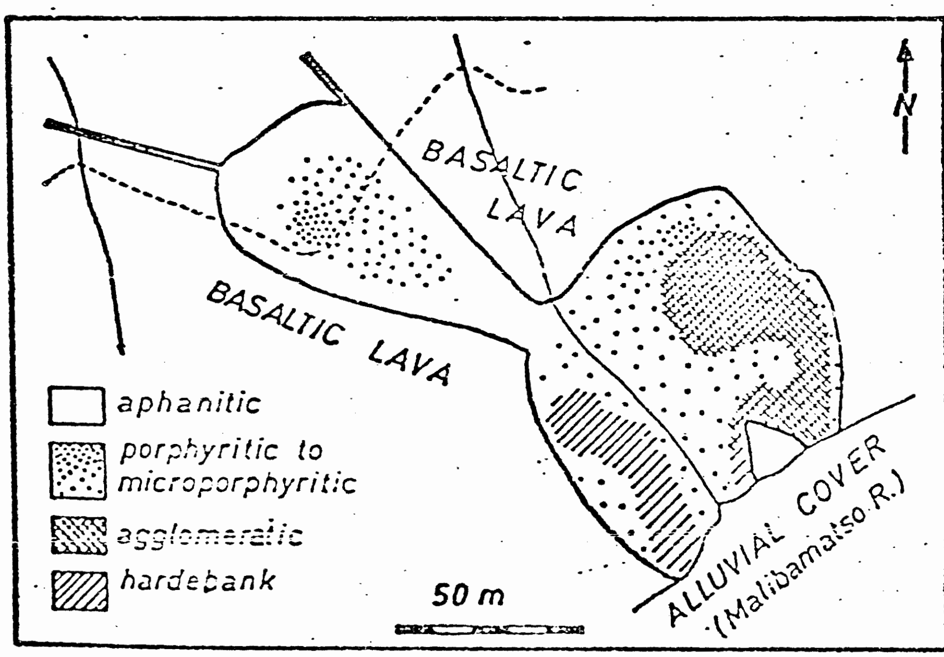


Figure 46 Geological map of Pipe 200.

FIG. 2.

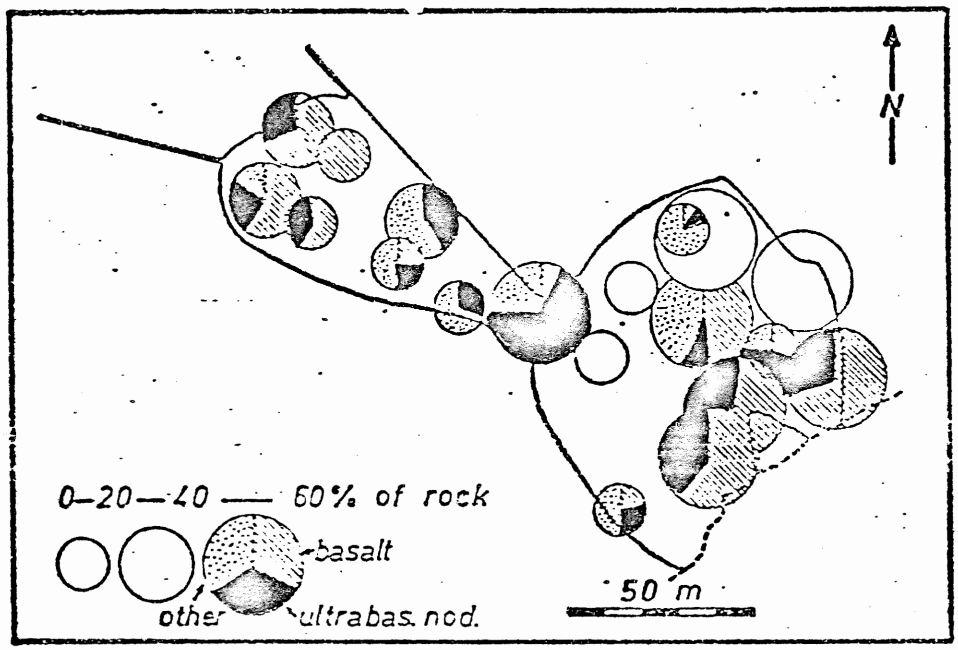


Figure 48 Abundance and relative frequency of inclusions in Pipe 200, observed in the field. Open circles indicate that the relative frequency was not determined.

of inclusions, where they consist predominantly of basalts. Northwest of the main pipe, ultramafic nodules are the most abundant inclusions, they constitute about 70% of the total (Fig. 2).

CHAPTER II: MINERALOGY AND TEXTURE OF PTH NODULES

General petrology of garnet lherzolites of the subset nodules

Pipe 200

The dominant minerals of the Pipe 200 subset nodules PTH 58, PTH 108, PTH 202, PTH 204, PTH 404, PTH 516 are olivine + orthopyroxene, constitutes about 80% of the rocks. Spinel, chrome diopside, chrome pyrope garnet and phlogopite make up the other 20%.

Olivines

Olivines are forsteritic in composition. Their grain sizes range from a fraction of 1 mm to 7 mm. The variation in grain sizes represents three generations of olivines independent of one another

a) large, deformed, strained primary crystals

b) smaller, strain-free recrystallized, grains

c) minute grains associated with cross-cutting veins

The recrystallized smaller grains are generally situated between grain boundaries, or in the case of minute grains, in veins. Medium size recrystallized olivines usually surround the phlogopite-chrome diopside-spinel pools. Olivine shapes are anhedral to subhedral, and subhedral forms are restricted to recrystallized grains.

Orthopyroxene

The 2.0-6.0 mm lobate, anhedral crystals of orthopyroxene constitutes 20-40% of the nodules. Grain sizes are predominantly medium-large, but small (1 mm) crystals are sometimes formed along grain boundaries and in the fractures of kelyphytized garnets. All orthopyroxenes are enstatites. The changes in their grain size represents a continuous cycle of deformation, recrystallization, grain growth (Harte *et al.*, 1975). During this cycle the mineral chemistry does not change and this continuous cycle takes place at constant temperature and pressure of an estimated 1050°C and 50 kbar.

Chrome Diopside

Most chrome diopside grains appear in clusters and discrete crystals are less common. Their size in the clusters is usually 1 mm, but in PTH 404 some appears as anhedral 'blebs' of 2 mm size. The modes of occurrence of chrome diopsides are:

a) as part of the phlogopite-rich pools
b) as collars around garnets, or collars around kelyphytic rims of garnets
c) as discrete grains (some with symplectic intergrowth of spinel), mostly associated with garnets,

but not as rims.

In the clusters, clinopyroxene cores are clear, but the margins are clouded. Small tubules are characteristic features of the rims, giving a spongy, serrated appearance to the edges. The tubules appear to be free of fluid inclusions, but small solid inclusions are common near the rims. These are too small to identify, they are brown, some opaque, and may be spinel and/or rutile. Although fluid inclusions are lacking in the rims, they are present in the core. The bright-green chrome diopsides constitute about 1-5% of the whole rock composition.

Garnets

Garnets are present in PTH 404, 204, 202 and 26-34. Other rocks, as PTH 58 and PTH 516 contain only spherically shaped kelyphytized areas (that are suggestive of the former presence of garnets), or subrounded pools. Grain shapes are crudely spherical, and their size ranges from 2.0-5.0 mm in diameter. Kelyphytic rims, rims of chrome spinel and/or collars of chrome diopsides and phlogopites are present on all garnets. In some instances brown opaque kelyphytes almost completely replace the garnets.

Spinel

Chrome spinels are predominantly associated with the kelyphytic rims of garnets, and with the pools of phlogopites and chrome diopsides. There is a distinct difference in crystal shape between these two different modes of occurrence. Spinels on garnet rims tend to occur as octahedra, while spinels associated with the pools are subrounded and 'worm-shaped'. Sizes range between 0.1-0.5 mm. In the pools, they are poikilitically enclosed by chrome diopsides and phlogopites, and rarely constitute more than 5% of the pools. Sometimes cpx shows a symplectic intergrowth with spinel. All spinels are black or dark brown.

Phlogopite

Phlogopites appear as (a) reaction rims around garnets (b) as major constituents of the pools, (c) as minute crystals in veins, (d) and less frequently as small, discrete grains. Where part of the pools, they form mosaic texture with chrome diopsides. In a number of pools the outer margins of phlogopites are chloritized, and in PTH 516 a wide vein connects two individual pools. In rock PTH 108 the centre of one pool consists of minute crystals of phlogopites, while surrounding grains are up to 1.5 mm in size. Deformation and undulose extinction are common features of the phlogopites in all rocks. Although the pools may be composed of up to 80% phlogopites, in the overall composition of the nodules they do not exceed 2-3%.

Textural Classification of PTH Nodules

The olivine-rich xenoliths of kimberlites and basalts are classified by Harte according to their deformation and recrystallization texture. This type of textural classification places the subset nodules of Pipe 200 into the "coarse-tabular" and the "porphyroclastic" groups. The characteristic-features of the two group types are as follows:

Coarse - Describes a rock that consists of minerals of 2.0 mm or more in size, with straight, smoothly curved or less regular grain boundaries. The commonly observed undulose extinction is evidence of strain. A limited amount of recrystallization is apparent, particularly in olivines. The sub-type 'tabular' describes mineral grains that show unequal dimensions. This term is also used for describing a texture where the grains have an approximately parallel orientation in addition to their unequal dimensions.

"Porphyroclastic" - The term describes a rock containing more than 10% olivine porphyroclasts in a finer grained matrix. The transition from coarse to porphyroclastic texture takes place on the first appearance of a porphyroclast "where a large grain or grain aggregates are completely surrounded by small grains" (Harte, 1976). Porphyroclastic rocks may be described as fine to medium grained, according to the grain sizes in the matrix. There may be several sub-types such as mosaic, disrupted, or laminated, but none of these sub-types is applicable to the subset nodules of Pipe 200.

Texture of the subset Nodules of PTH

Textural features common to all subset nodules are recrystallization, polygonization, grain deformation, mosaic texture where pools are present, and the almost complete lack of poikiloblasts. Kelyphytic rims are present on all garnets - to different extent, and kelyphytic rims may have collars of chrome diopsides and phlogopites. The most extensively recrystallized rock is PTH 404, where olivine grain sizes vary between a fraction of 1.0 mm and 7.0 mm. A second generation of olivines (< 1.0 mm) cut the recrystallized, polygonized medium sized grains, indicating a second event of recrystallization. The larger grains are sometimes completely surrounded by smaller grains, placing this rock into Harte's "porphyroclastic" group. Considerable elongation of orthopyroxenes and olivines in rock PTH 516 is apparent. Some olivines are polygonized, recrystallized, particularly when adjacent to the phlogopite and chrome diopside-rich pools. A number of pools are surrounded by large orthopyroxenes. Since orthopyroxenes recrystallize less readily than olivines, they may confine the occasional pools to their original spherical space. Elongation of phlogopite-rich pools suggests severe straining. A similarly elongated pool in PTH 516 consists predominantly of chrome diopside, a substantial amount of spinel, and less that 5% phlogopite. Both types of elongated pools are surrounded by recrystallized olivines. This feature, together with the strained nature of phlogopites, olivines and orthopyroxenes makes rock PTH 516 a transition between the "coarse-tabular" and the "porphyroclastic" texture.

PTH 108 resembles PTH 404 in texture. In both instances a second event of recrystallization is apparent. There are minute grains of olivines in veins, cross-cutting the previously recrystallized and polygonized olivines. In PTH 404, a wide vein contains only small, granoblastic, polygonal arrays of olivines.

Generally, phlogopites in the pools show relatively straight grain-boundaries with triple junctions. In some cases both phlogopites and chrome diopsides are strained. Collars of diopsides and phlogopites on garnets show strained and undulose extinction as well. Polygonization of olivines is a common feature in all rocks, while in orthopyroxenes it is a rare phenomenon. Where it does occur, the strain-free orthopyroxenes form granoblastic, polygonal texture. These are usually adjacent to and/or surround the larger, strained grains of orthopyroxenes.

CHAPTER III: MINERAL CHEMISTRY

METHOD OF ANALYSIS

The ultramafic rocks of Pipe 200 have been analyzed by electron microprobe at Dalhousie University, and a summary of their average chemical composition is presented in the paper of Carswell et al. (1979). Phlogopites were not included in the original analysis, but will be added later, since they are an important part of the topic discussed in this thesis. Additional analyses were necessary on chrome diopsides to check for chemical zonation on the grains in and outside of the pools. Phlogopites and chrome diopsides were analysed in six rocks; four or five grains of each mineral in every rock, and 3-5 points were analysed on each grain. The point analyses were performed systematically from core to rim in the phlogopites and chrome diopsides. The purpose of the point analysis was to detect tendencies of certain elements to increase or decrease from core to rim. The results are summarized in Tables 1 to 5, and graphically illustrated in Figures 3, 4, 5, and 6. Phlogopites show a slight tendency to increase in Al_2O_3, and TiO_2, Cr_2O_3 towards the rim. Point analyses of chrome diopsides do not reveal any particular tendency to increase or decrease in elements from core to rim. To

TABLE 1

ANALYSIS OF Cr. DIOPSIDES FROM CORE TO RIM

	404					9					108			
	Core				Rim	Core				Rim	Core			Rim
SiO_2	53.91	54.03	53.54	53.92	53.91	54.31	54.01	50.99	52.23	53.29	54.14	54.38	54.44	54.27
Al_2O_3	2.34	2.24	2.48	2.21	2.34	3.25	3.38	3.17	3.71	2.20	1.35	1.44	0.98	1.36
Cr_2O_3	2.73	2.77	2.72	2.84	2.76	3.49	3.68	3.75	3.70	3.24	3.22	3.34	3.05	2.84
FeO	2.32	2.31	2.54	2.37	2.42	2.36	2.54	3.20	2.85	2.51	2.38	2.30	2.43	2.37
MnO	0.17	0.13	0.11	0.10	0.15	0.08	0.13	0.09	0.15	0.08	0.12	0.18	0.05	0.07
NiO	0.17	0.13	0.08	0.21	0.12	0.09	0.12	0.20	0.20	0.00	0.13	0.18	0.05	0.03
MgO	16.23	16.30	16.57	16.50	16.42	15.25	15.93	19.54	17.48	16.84	16.21	16.35	16.61	16.67
CaO	19.65	19.66	19.33	19.66	19.65	18.14	17.55	14.49	16.07	18.13	20.63	20.36	20.65	20.46
Na_2O	2.43	2.38	2.24	2.60	2.42	3.63	3.81	3.09	3.69	2.63	2.24	2.33	2.02	1.98

TABLE 2

ANALYSIS OF PHLOGOPITES FROM CORE TO RIM

	516					9					108				
	Core				Rim	Core				Rim	Core				Rim
SiO_2	42.13	42.43	42.83	42.47	42.04	39.71	40.32	40.38	40.77	40.51	42.30	42.52	42.72	42.44	42.36
TiO_2	0.55	0.41	0.51	0.46	0.79	0.29	0.17	0.37	0.18	0.32	0.18	0.21	0.32	0.19	0.27
Al_2O_3	12.06	12.17	12.22	11.12	12.89	12.95	12.83	13.13	10.44	13.15	11.96	12.42	12.64	12.67	12.50
Cr_2O_3	0.63	0.57	0.77	0.72	1.06	1.23	1.16	1.49	2.04	1.40	0.80	0.82	0.98	0.87	0.98
FeO	2.77	2.85	2.74	3.40	3.11	2.50	2.47	2.66	2.89	2.73	2.71	2.58	2.79	2.89	2.65
MgO	26.16	26.31	26.13	27.54	26.08	24.56	25.21	24.94	24.79	24.79	26.85	26.37	26.47	25.94	26.50
Na_2O	-	-	-	-	-	0.15	-	0.19	0.36	0.38	-	-	-	-	-
K_2O	10.19	10.26	10.34	9.06	10.14	9.30	9.50	9.45	9.43	9.49	9.66	10.34	10.08	10.25	10.13

TABLE 3

POINT ANALYSIS OF AV. PHLOGOPITE COMPOSITION IN PTH 516, PTH 9, PTH 108

	Core				Rim
SiO_2	41.38	41.77	41.86	41.89	41.64
TiO_2	0.34	0.26	0.40	0.28	0.45
Al_2O_3	12.32	12.47	12.66	11.41	12.85
Cr_2O_3	0.89	0.85	1.08	1.20	1.19
FeO	2.66	2.63	2.73	3.05	2.83
MgO	25.86	25.96	25.85	26.08	25.79
Na_2O	-	-	-	-	-
K_2O	9.72	10.03	9.96	9.58	9.92

POINT ANALYSIS OF AVERAGE CHROME DIOPSIDE COMPOSITION PTH 404, PTH 9, PTH 108

	Core				Rim
SiO_2	54.12	54.14	52.99	53.53	53.60
Al_2O_3	2.31	2.35	2.21	2.43	2.27
Cr_2O_3	3.15	3.26	3.17	3.13	3.00
FeO	2.35	2.41	2.72	2.53	2.47
MnO	0.12	0.15	0.08	0.08	0.11
NiO	-	-	-	-	-
MgO	15.90	16.20	17.57	16.88	16.63
CaO	19.47	19.19	18.16	18.73	18.89
Na_2O	2.77	2.84	2.45	2.76	2.53

TABLE 4

CHEMICAL ANALYSIS OF PHLOGOPITES OF

THE PTH SUBSET NODULES

Sample Number	516	108	58	9	204	26-34
Rock Type	CL	CL	GCL	CL	GCL	GL
SiO_2	42.39	42.48	41.16	40.29	40.26	41.26
Al_2O_3	12.01	12.38	13.18	12.39	14.92	10.20
TiO_2	0.51	0.23	0.29	0.25	0.22	0.74
Cr_2O_3	0.79	0.88	1.03	1.45	1.11	-
FeO	3.38	2.71	2.60	2.61	2.31	7.48
MgO	26.48	26.49	25.00	24.85	24.22	24.46
Na_2O	0.07	-	1.16	0.17	0.80	-
K_2O	9.99	10.03	9.80	8.66	9.83	9.16

STRUCTURAL FORMULAE ON THE BASIS

OF 22 OXYGENS

Si	5.9629	5.995	5.877	5.930	5.765	6.042
Al^{iv}	1.9915	2.005	2.123	2.070	2.235	1.762
Al^{vi}	-	0.005	0.095	0.080	0.284	-
Ti	0.0541	0.003	0.031	0.027	0.024	0.109
Cr	0.0829	0.098	0.117	0.168	0.126	-
Fe	0.3973	0.320	0.311	0.321	0.277	0.916
Mg	5.5512	5.564	5.319	5.451	5.168	5.338
Na	0.0186	-	0.321	0.047	0.224	-
K	1.7938	1.804	0.784	1.626	1.796	0.712

CL = Chrome Lherzolite

GCL = Garnet Chrome Lherzolite

TABLE 5

CHEMICAL ANALYSIS OF CHROME DIOPSIDES OF PTH SUBSET NODULES (Based on the average 4 grains in each rock)

Sample Number	516	108	58	9	204	404
Rock Type	CL	CL	GCL	CL	GCL	GCL
SiO_2	52.70	54.31	55.32	52.97	54.51	53.86
Al_2O_3	1.82	1.28	2.52	3.14	4.45	2.32
Cr_2O_3	2.86	3.11	2.95	3.56	3.10	2.76
FeO	2.49	2.37	2.04	2.69	1.99	2.39
MnO	-	0.11	-	0.07	-	0.13
NiO	-	0.10	-	0.13	-	0.14
MgO	14.87	16.46	15.95	17.01	13.60	16.40
CaO	19.15	20.53	19.06	16.88	19.95	19.59
Na_2O	2.64	2.14	2.61	3.37	3.29	2.42

STRUCTURAL FORMULAE ON THE BASIS OF 6 OXYGENS

Si	1.985	1.971	1.987	1.928	1.988	1.952
Al^{iv}	0.015	0.029	0.013	0.072	0.042	0.048
Al^{vi}	0.066	0.026	0.094	0.062	0.147	0.051
Cr	0.085	0.089	0.084	0.102	0.088	0.079
Fe	0.078	0.072	0.061	0.032	0.059	0.073
Mn	-	0.003	-	0.002	-	0.004
Ni	-	0.003	-	0.004	-	0.004
Mg	0.835	0.890	0.854	0.923	0.728	0.886
Ca	0.773	0.798	0.734	0.658	0.768	0.761
Na	0.193	0.150	0.182	0.238	0.229	0.205

CL = Chrome Lherzolite

GCL = Garnet Chrome Lherzolite

Figure 3

Average core to rim analysis of Chrome Diopsides (from PTH404, PTH9, PTH108)

wt. % Na_2O
Al_2O_3
Cr_2O_3

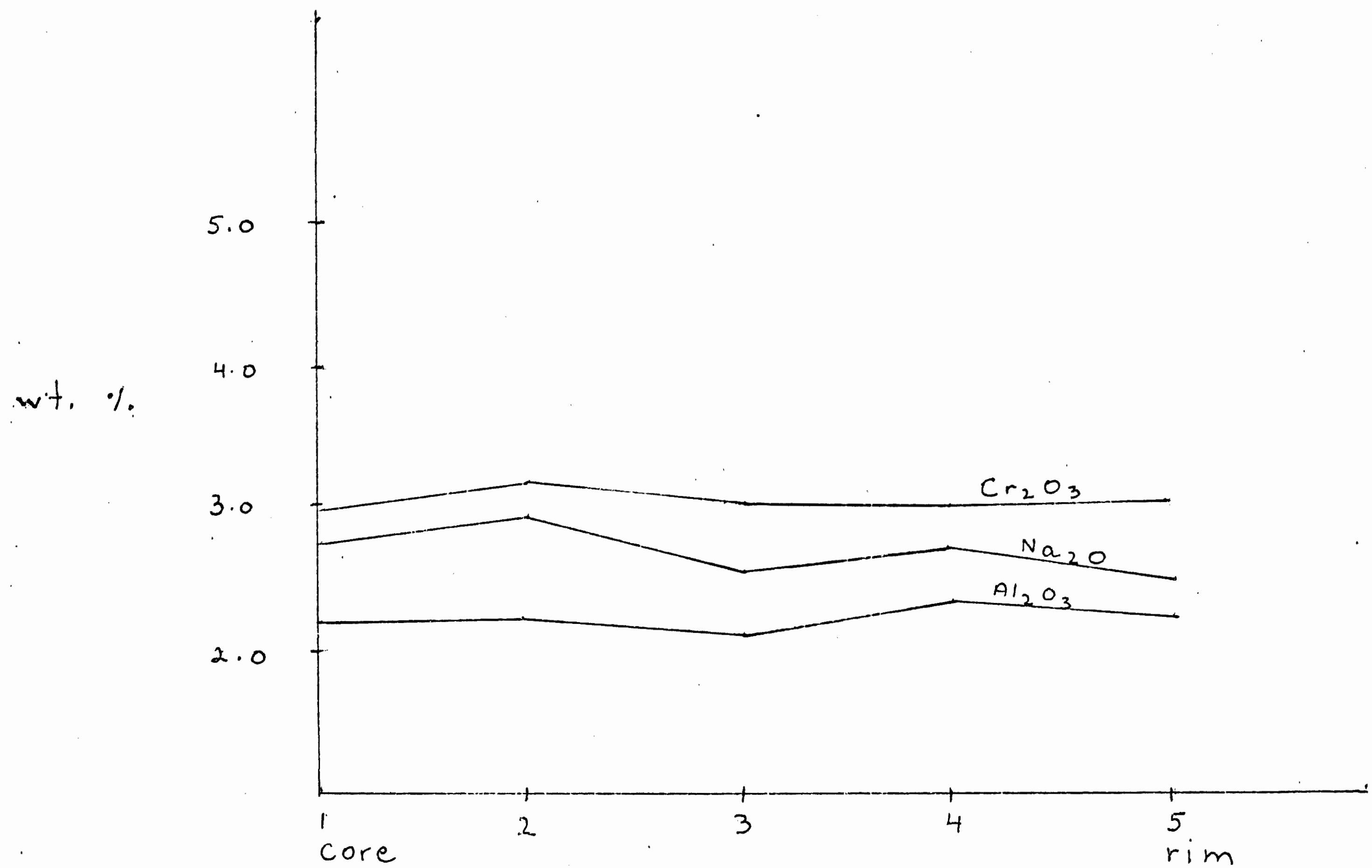


Figure 4

Average core to rim analysis of Chrome Diopsides (PTH404, PTH9, PTH108)

wt. % CaO-MgO

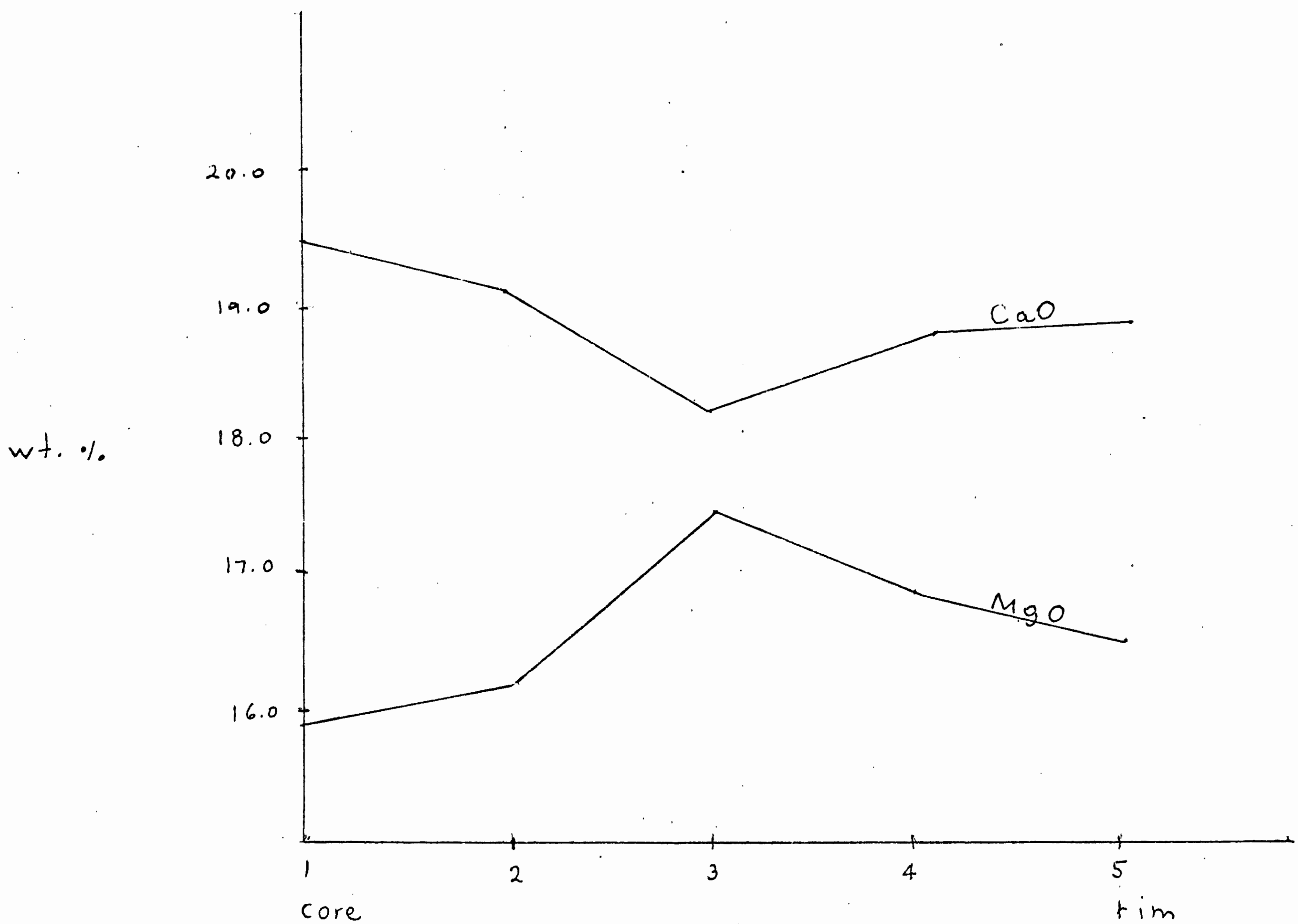


Figure 5

Average core to rim analysis of Phlogopites (PTH516, PTH9, PTH108)

wt. % Al_2O_3
K_2O
FeO

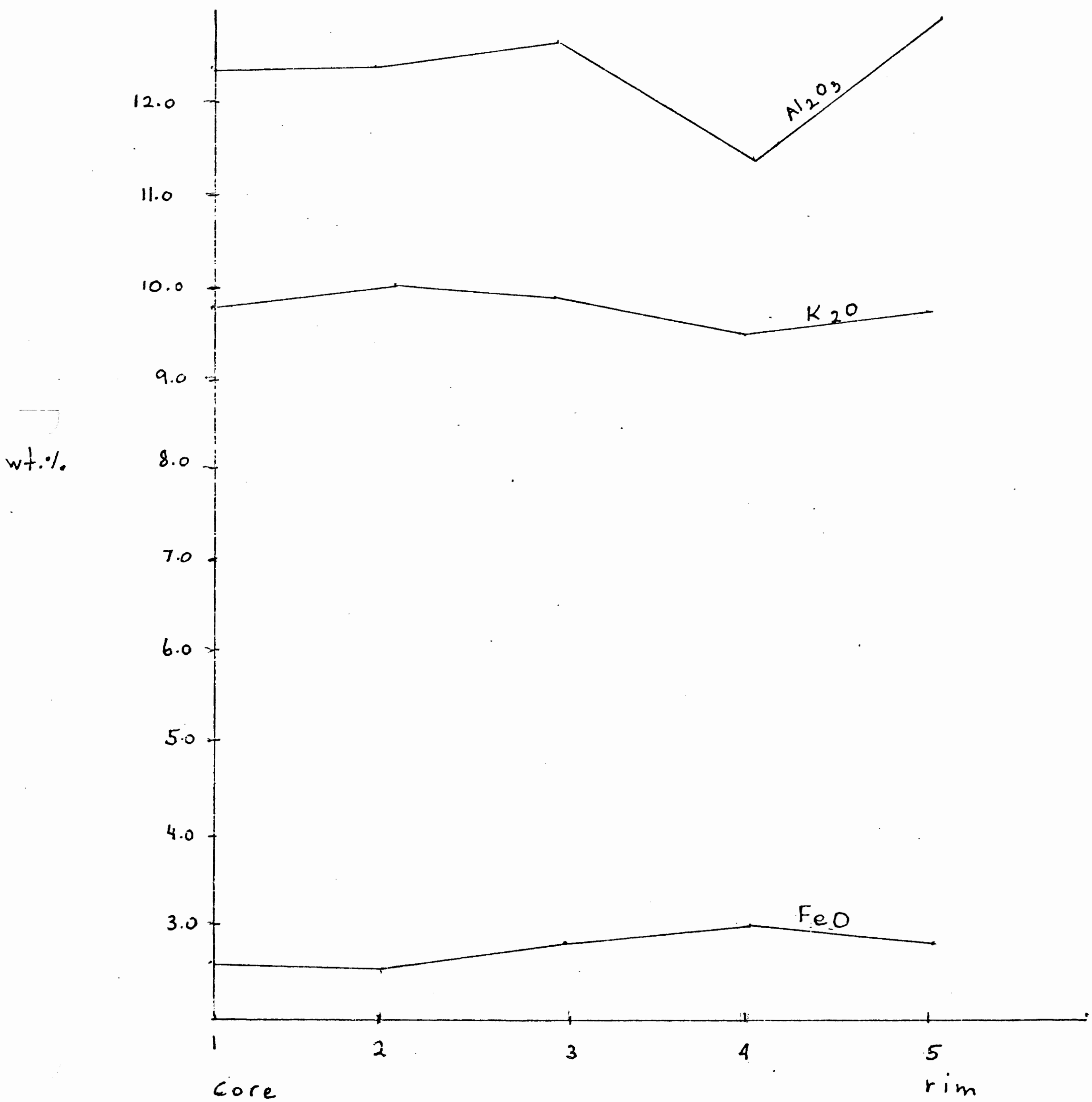


Figure 6

Average core to rim analysis of Phlogopites (PTH516, PTH9, PTH108)

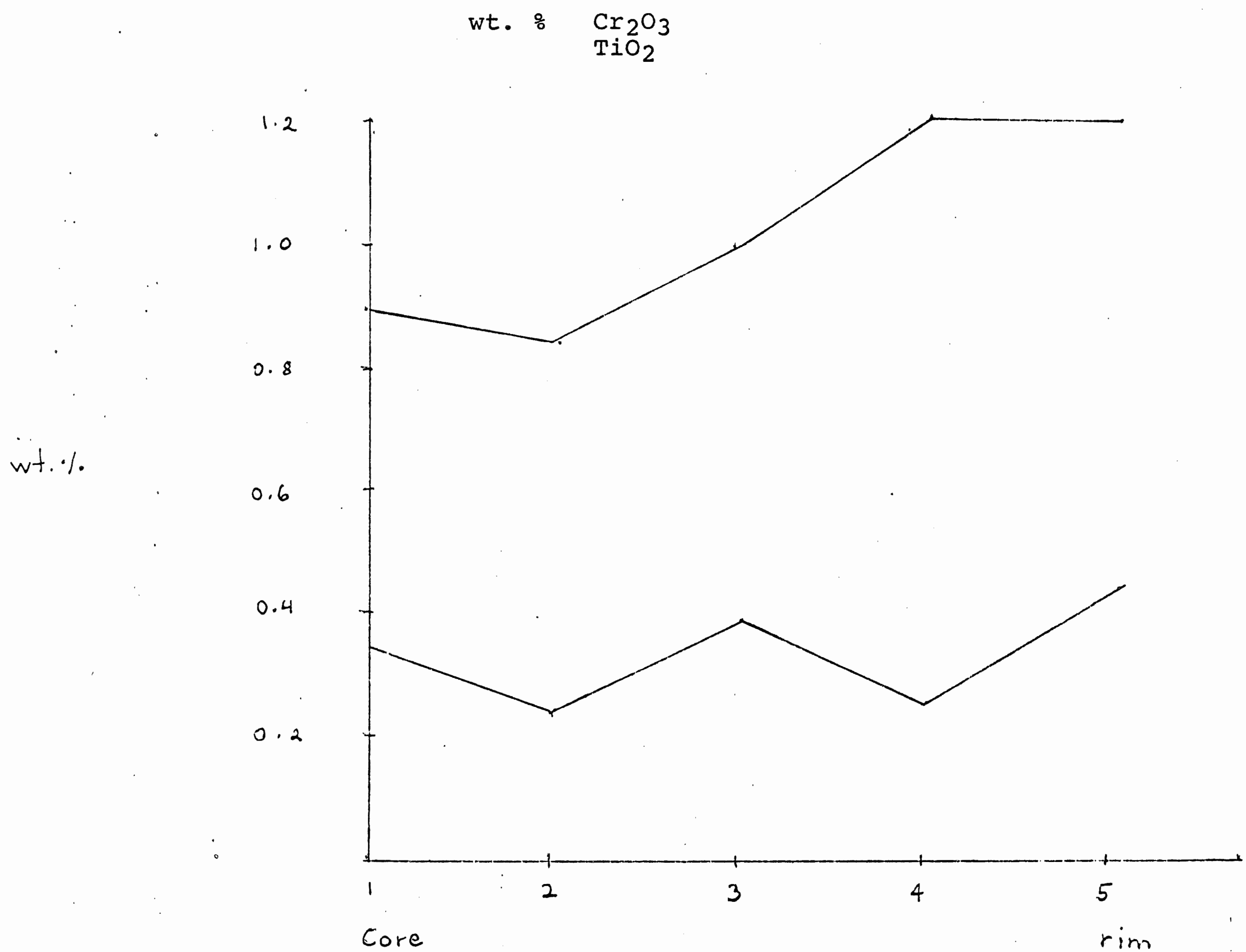


TABLE 6.

ANALYSIS OF DIOPSIDES FROM CORE TO RIM

TOWARDS OPX, PHLOGOPITE, OLIVINE

Average, From PTH 108,516

	To OPX			To PHLOGOPITE			To OLIVINE		
	Core		Rim	Core		Rim	Core		Rim
SiO_2	52.23	52.79	52.32	52.39	52.59	52.84	52.38	52.83	52.86
Al_2O_3	1.73	1.79	1.70	1.81	1.50	1.68	1.46	1.66	1.71
Cr_2O_3	2.81	2.95	2.94	2.81	2.97	3.23	2.89	2.94	2.89
FeO	2.41	2.51	2.72	2.40	2.39	2.37	2.47	2.41	2.40
MgO	14.72	14.82	15.12	14.75	14.95	14.89	14.82	14.88	14.85
CaO	20.09	20.26	19.50	20.32	20.53	20.51	20.21	20.46	20.52
Na_2O	2.48	2.62	2.57	2.47	2.42	2.56	2.39	2.61	2.57

test for a possible exchange of elements between chrome diopsides and their neighbour minerals, further analyses were necessary. Within one grain 3 points were analyzed from core to rim in the directions of olivine, orthopyroxene and phlogopite. The results are summarized in Table 6.

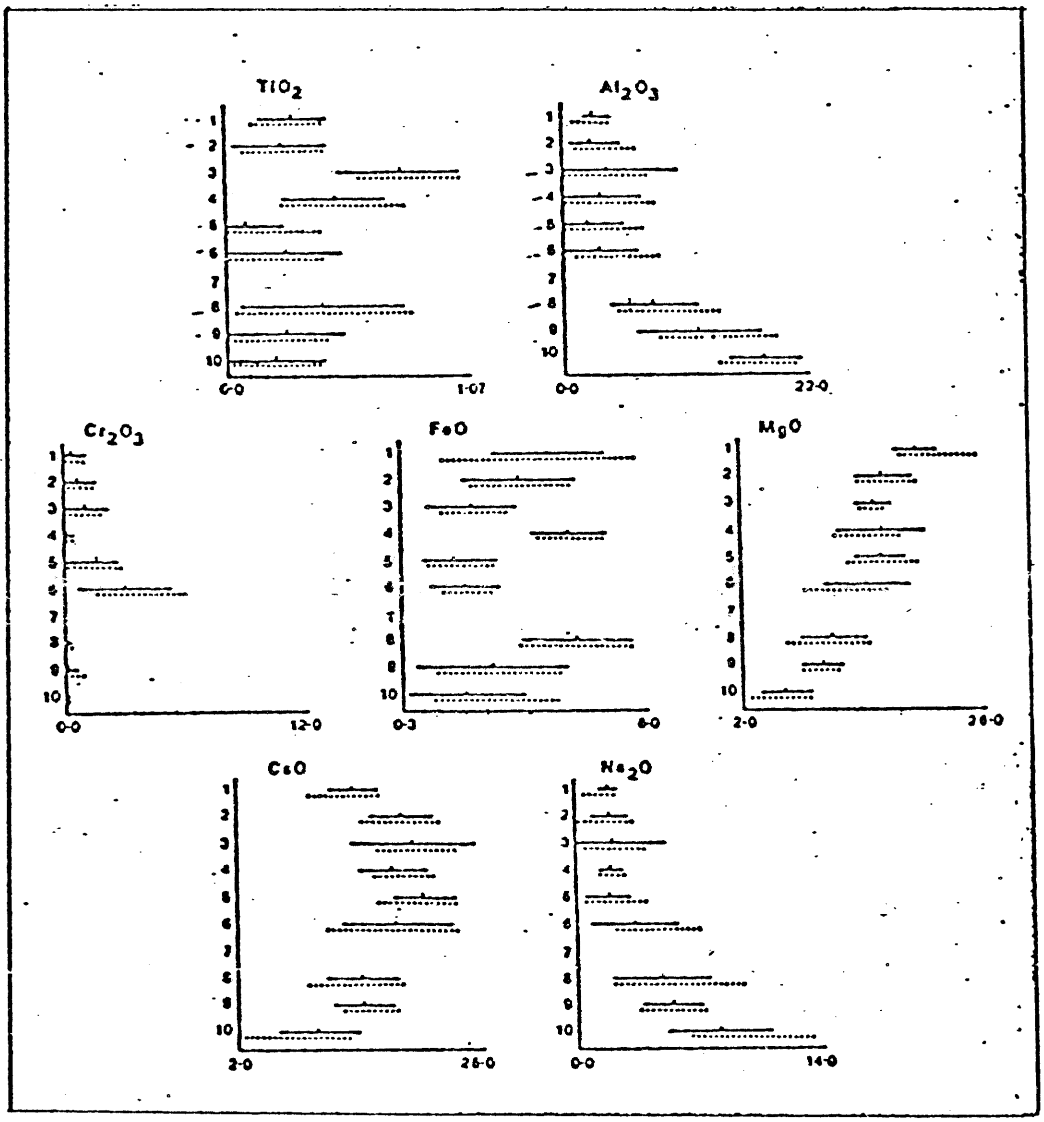
ANALYSIS AND CLASSIFICATION OF THE PIPE 200 SUBSET NODULES BY THEIR MINERAL CHEMISTRY

Diopsides

Diopsides in the subset nodules of Pipe 200 were classified by the method of Stephens and Dawson (unpubl.) According to the chemical composition (TiO_2, Al_2O_3, Cr_2O_3, FeO, MgO, CaO, Na_2O), they belong to groups 5 and 6 "chrome diopsides" and "ureyitic diopsides", respectively. Both groups are characterised by relatively high Cr_2O_3. There is a positive correlation between Al_2O_3 and Na_2O, and between Na_2O and Cr_2O_3 in the chrome diopside group. In the ureyitic diopside group the positive correlation is restricted to Na_2O and Al_2O_3. These two types of chrome diopsides occur mainly in the mineral assemblages of garnet lherzolites and garnet-olivine pyroxenites.

Carswell analysed a number of diopsides in the rock he used for his phlogopite classification, and observed

CPX DISCRIMINATOR



STEPHENS AND DAWSON

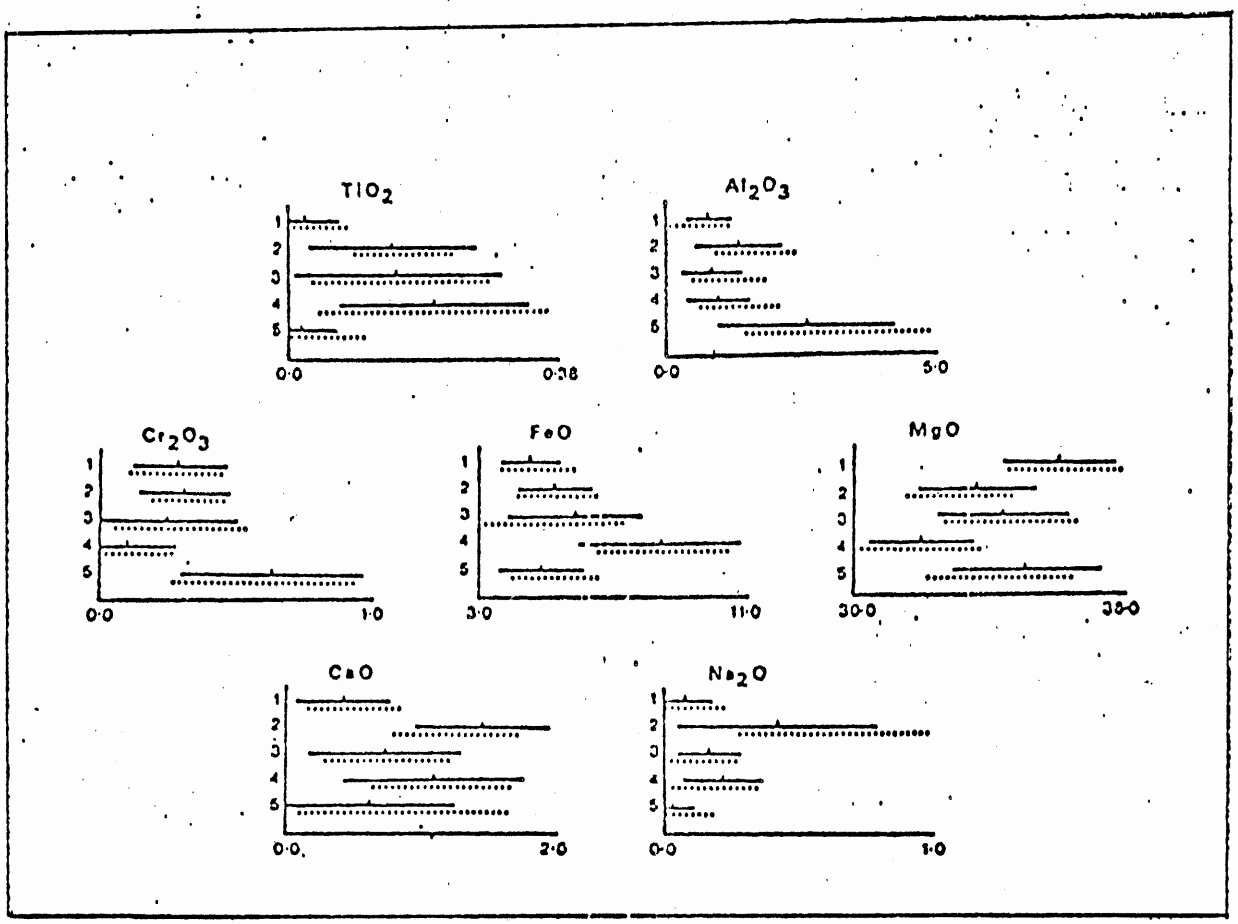
that a sharp decrease in Na_2O and Al_2O_3 content occurs towards the rim. He thought that the porous, cloudy rims of his clinopyroxenes then may be the result of decompression, since they are depleted in jadeite components.

The diopsides of the Pipe 200 subset nodules differ from Carswell's diopsides. The decrease in Al_2O_3 and Na_2O from core to rim is not apparent (Fig. 3).

Orthopyroxene

The orthopyroxene of the Pipe 200 subset nodules according to the classification of Stephens and Dawson (unpublished) belong to groups number 1 and 3. Both of these groups occur in garnet lherzolites and olivine pyroxenites. They are dominated by enstatites with a Mg (Mg + Fe) ratio of approximately 0.93. There is low TiO_2 content (0.02%) in group 1, and a somewhat higher percent in group 3. Positive correlation exists between MgO and Cr_2O_3 in both groups. In addition there is positive correlation in group 3 between TiO_2 and Al_2O_3, and TiO_2 and Na_2O. Negative correlation exists between CaO and Al_2O_3, and MgO and Cr_2O_3 in group 1.

OPX DISCRIMINATOR



W. E. STEPHENS & DAWSON

Garnet

The garnets were also classified by Dawson and Stephens (1975) according to their chemical composition. Their classification by the flow-sheet method places the garnets of the Pipe 200 subset nodules into group 9. The characteristic features of group 9 are as follows: they are titanium-poor pyrope garnets with moderate amount of Cr_2O_3 (3.5%), low CaO (5.15%). MgO correlates negatively with CaO, FeO, Cr_2O_3. Positive correlation exists between CaO and Cr_2O_3, and MgO and Al_2O_3. These garnets are from the four-phase garnet lherzolites, and they are considered to be the most common type of xenoliths found in kimberlites. According to Dawson and Stephens (1975) these garnets sometimes belong to the diamontiferous garnet lherzolites.

Phlogopite

The average chemical composition of phlogopites in the PTH nodules may be compared to the composition of Carswell's (1975) primary and secondary phlogopites. A comparison between the chemistry of the phlogopites of subset nodules of Pipe 200 and the phlogopites of Carswell is shown in Table 8.

Carswell used TiO_2, Al_2O_3, Cr_2O_3, and SiO_2 as

GARNET CLASSIFICATION

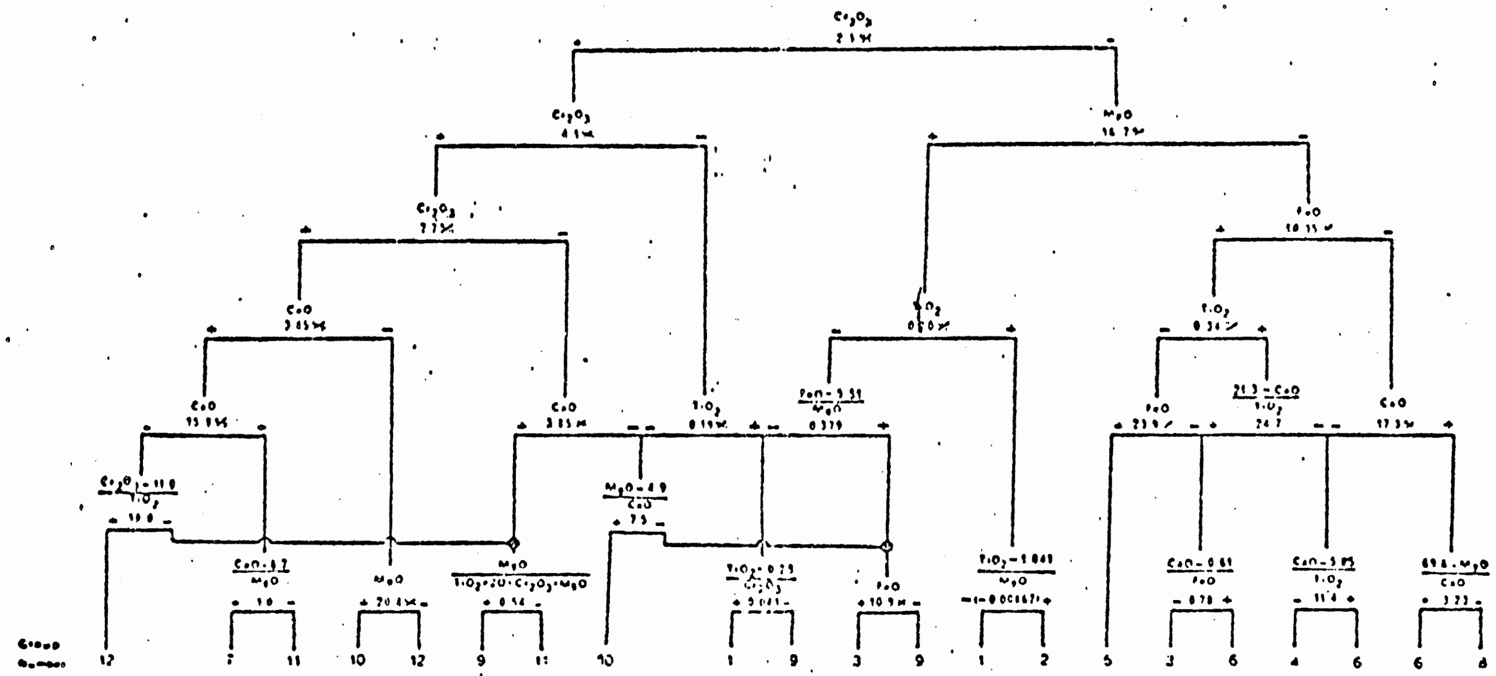


FIG. .—Flow sheet for the simple classification scheme. Starting with Cr_2O_3, evaluate the pertinent oxide or oxide ratio and follow the flow sheet in the direction of the result in relation to the stated value on the flow sheet. In the case of equality, either branch may be followed but the composition of the sample should be carefully checked against the oxide ranges of the group to which it is finally allocated (see Appendix and fig. 2).

TABLE 1. PRIMARY PHLOGOPITES

Wt.%	CK1	CK2	CK3	CK4	CB6
SiO_2	40.7	41.2	41.1	41.5	41.7
TiO_2	0.28	0.22	0.15	0.26	0.68
Al_2O_3	12.8	12.4	13.2	12.5	12.2
Cr_2O_3	0.86	0.70	0.60	0.75	0.61
*FeO	2.63	2.64	2.56	2.52	2.78
MnO	0.01	0.05	0.01	0.03	0.02
MgO	26.5	26.6	27.9	26.5	26.5
CaO	0.02	0.02	0.02	0.01	0.01
Na_2O	0.75	0.76	0.99	0.91	0.31
K_2O	9.31	9.32	8.78	9.16	10.2
Total	93.9	93.9	95.3	94.1	95.0

*FeO—total iron as FeO
CK—samples from Kimberley Mines
CB—samples from Bultfontein Dumps

STRUCTURAL FORMULAE CALCULATED ANHYDROUS WITH RESPECT TO TWENTY-TWO OXYGENS

	CK1		CK2		CK3		CK4		CB6	
Si^{4+}	5.82	7.93	5.89	7.97	5.77	7.96	5.90	7.99	5.90	7.94
Al^{3+}	2.16		2.08		2.19		2.09		2.04	
Ti^{4+}	0.030	6.09	0.024	6.07	0.032	6.23	0.028	6.03	0.072	6.06
Cr^{3+}	0.098		0.079		0.066		0.084		0.068	
Fe^{2+}	0.314		0.315		0.300		0.300		0.329	
Mn^{2+}	0.001		0.005		0.001		0.003		0.003	
Mg^{2+}	5.65		5.65		5.83		5.62		5.59	
Ca^{2+}	0.003	1.91	0.003	1.91	0.003	1.84	0.002	1.91	0.002	1.93
Na^{+}	0.208		0.211		0.270		0.251		0.085	
K^{+}	1.70		1.70		1.57		1.66		1.84	
Fe^{2+}/Mg^{2+}	0.056		0.056		0.051		0.053		0.059	
Na^{+}/K^{+}	0.123		0.124		0.172		0.151		0.046	

TABLE 2. SECONDARY PHLOGOPITES

Wt.%	CK1	CK3	CK4	CB4	CB6
SiO_2	39.7	39.0	39.2	39.1	39.3
TiO_2	1.45	0.45	0.86	1.36	1.41
Al_2O_3	13.9	16.1	14.5	15.1	14.8
Cr_2O_3	1.60	1.51	1.36	1.57	1.50
*FeO	3.12	3.15	3.17	2.95	2.90
MnO	0.10	0.02	0.14	0.05	0.02
MgO	24.8	25.3	24.5	25.1	24.7
CaO	0.03	0.02	0.03	0.02	0.03
Na_2O	0.92	1.41	1.82	1.05	0.92
K_2O	9.06	7.87	7.38	8.41	9.14
Total	94.7	94.8	93.0	94.7	94.7

*FeO—total iron as FeO
CK—samples from Kimberley Mines
CB—samples from Bultfontein Dumps

STRUCTURAL FORMULAE CALCULATED ANHYDROUS WITH RESPECT TO TWENTY-TWO OXYGENS

	CK1		CK3		CK4		CB4		CB6	
Si^{4+}	5.65	7.99	5.52	8.00	5.65	8.00	5.54	8.00	5.59	8.00
Al^{3+}(IV)	2.34		2.43		2.35		2.45		2.41	
Al^{3+}(VI)	—	5.99	0.194	6.11	0.114	6.01	0.071	6.06	0.076	5.97
Ti^{4+}	0.155		0.048		0.093		0.145		0.151	
Cr^{3+}	0.180		0.168		0.154		0.176		0.169	
Fe^{2+}	0.371		0.372		0.382		0.350		0.345	
Mn^{2+}	0.012		0.003		0.017		0.006		0.003	
Mg^{2+}	5.27		5.32		5.25		5.31		5.30	
Ca^{2+}	0.004	1.91	0.003	1.81	0.004	1.87	0.003	1.81	0.004	1.92
Na^{+}	0.253		0.386		0.509		0.288		0.253	
K^{+}	1.65		1.42		1.36		1.52		1.66	
Fe^{2+}/Mg^{2+}	0.070		0.070		0.073		0.066		0.066	
Na^{+}/K^{+}	0.154		0.272		0.376		0.189		0.153	

TABLE 8

AVERAGE PHLOGOPITE COMPOSITION

	Av. Carswell Primary	Av. Carswell Secondary	516	9	108	58	204	Kimberlite
SiO_2	41.24	39.26	42.39	40.29	42.48	41.16	40.26	41.26
TiO_2	0.32	1.11	0.51	0.25	0.23	0.29	0.22	0.74
Al_2O_3	12.62	14.88	12.01	12.39	12.38	13.18	14.92	10.20
Cr_2O_3	0.70	1.51	0.74	1.45	0.88	1.03	1.11	0
FeO	2.63	3.06	3.38	2.61	2.71	2.60	2.31	7.48
MgO	26.80	24.88	26.48	24.85	26.49	25.00	24.22	24.46
Na_2O	0.74	1.22	0.07	0.17	-	1.16	0.80	-
K_2O	9.35	8.37	9.99	8.66	10.03	9.80	9.83	9.16

criteria for placing phlogopites into the primary and secondary groups. His primary phlogopites have lower TiO_2, Al_2O_3, Cr_2O_3, and higher SiO_2 contents. By using Carswell's classification, we arrive at the conclusion that PTH subset nodules contain only primary phlogopites. Analyzed grains include grains from different textural areas; from pools, from collars on spinel and garnets. In general, TiO_2 content is a low 0.32%, while SiO_2 content is high 41.58%. For comparison, chemical analysis was performed on phlogopites from the kimberlite matrix of rock 26-34 (Table 8). The TiO_2 content average 0.74%, closer to the 1.11% average of Carswell's secondary phlogopites. (Table 7).

CHAPTER IV: DISCUSSION

The Pipe 200 subset nodules differ from the rest of the PTH nodules in that they contain garnets with collars of chrome diopsides, phlogopites and spinel (PTH-58) and 'pools' of the same mineral assemblage. Pools, however, do not contain garnets (PTH-516, PTH-108).

The "Summary of Observations" (Table 9-10) lists the characteristic features of the collars on garnets and of the pools, taking into consideration a) texture b) chemistry c) mineral association.

Collars on Garnets (PTH-58)

The collars are aggregates of chrome diopside, phlogopite and spinel on the outer rims of garnets. The garnets are kelyphytized. Grain sizes of phlogopites and chrome diopsides vary between 0.2-0.5 mm. Spinel grain sizes are between a fraction of a millimeter and 0.3 mm.

Chrome diopsides are bright-green with clear cores and spongy, frothy margins. They constitute about 60-70% of the collars. A number of phlogopite grains are strained and deformed. Spinels are ehuedral, and some are enclosed in phlogopites. The occasional spinels are surrounded by minute grains of phlogopite, and their texture and size

TABLE 9

SUMMARY OF OBSERVATIONS

Mineralogy, texture and chemistry of collars on garnets

1. <u>Mineral association</u>	chrome diopside + phlogopite + spinel + garnet
2. Shape of collar + garnet	spherical
3. Average phlogopite grain size	0.2-0.5 mm
4. Average chrome diopside grain size	0.3 mm
5. <u>Texture</u>	collars on kelyphytized garnets
6. Texture of chrome diopsides	Spongy, frothy margins, clear core
7. Texture of phlogopites	Strained
8. Texture of spinels	Euhedral
9. Textural features present in all collars and kelyphytized garnet associations	recrystallization, grain deformation, kelyphytization
<u>Chemistry</u>	
10. Average chemical composition of the whole rock	highly depleted
11. Spinel chemistry in collars	relatively high Al_2O_3 and low TiO_2 content
12. Classification of phlogopites according to chemical composition	primary (low TiO_2, high SiO_2 content)
13. Collars are common in PTH nodules	no

TABLE 10

SUMMARY OF OBSERVATIONS

Mineralogy, texture and chemistry of the 'pools'

1.	Mineral association	chrome diopside + phlogopite + spinel
2.	Shape of pools	Spherical (more or less)
3.	Average phlogopite grain size	0.5-1.0 mm
4.	Average chrome diopside grain size	0.5 mm
5.	Small fragment(s) of garnet present in centres of some pools	yes
6.	Texture of pools	mosaic
7.	Texture of chrome diopsides	Spongy, frothy margins, clear core
8.	Texture of phlogopites	Strained
9.	Texture of spinels	worm-shaped, fragmented
10.	Textural features present in all pools	recrystallization, grain deformation, mosaic texture
	Chemistry	
11.	Average chemical composition of the whole rocks	highly depleted
12.	Bulk composition of pools	K-rich (Fig.)
13.	Spinel chemistry in pools	Low Al_2O_3, high TiO_2
14.	Classification of phlogopites according to chemical composition (Carswell, 1975)	primary (low TiO_2, high SiO_2 content)
15.	Pools are common in PTH nodules	no

suggests different origin from the larger phlogopites in the collars. The minute aggregates are too small for chemical analysis by microprobe, but they are probably secondary phlogopites, the result of infiltration metasomatism related to the kimberlites. Chemical compositions determined for the phlogopites in collars show high SiO_2 and low TiO_2 content (Table 8). The composition of chrome diopsides are similar to the average composition of chrome diopsides in the PTH nodules. The chemistry of the euhedral spinels in the collars differ from the average chemistry of the spinels in the PTH nodules. The PTH-58 spinels have higher TiO_2, Cr_2O_3 and FeO contents, but they are lower in Al_2O_3 and MgO (Table 11, Clarke and Carswell et al.).

The 'pools', PTH-516, PTH-108

The pools in the PTH subset nodules are mineral aggregates of chrome diopside, phlogopite and spinel. Shape of the pools are more or less spherical, occupying areas of about 5 x 5 mm. The pools are not associated with garnets at the present. Phlogopites in the pools are medium size grains, ranging from 0.5-1.0 mm, and they form a mosaic texture with straight or slightly curved grain boundaries. Some phlogopites are strained and slightly deformed. Chrome diopsides have clear cores and spongy, frothy margins.

TABLE 11

CHEMICAL ANALYSES OF SPINEL IN THE SUBSET NODULES

Sample Number	516	58	Av. PTH Nodules
Rock Type	CL	GCL	
SiO_2	0.26	0.21	0.12
TiO_2	1.22	0.96	0.66
Al_2O_3	4.08	9.45	21.45
Cr_2O_3	59.19	54.08	45.27
FeO	21.62	18.94	15.56
MnO	0.09	0.16	-
MgO	11.21	13.20	15.93
CaO	0.07	0.10	-

STRUCTURAL FORMULAE ON THE BASIS OF 16 OXYGENS

Si	0.036	0.028
Ti	0.128	0.097
Al	0.669	1.501
Cr	6.538	5.785
Fe	2.515	2.134
Mn	0.011	0.018
Mg	2.326	2.653
Ca	0.010	0.014

CL = Chrome Lherzolite

GCL - Garnet Chrome Lherzolite

Their average grain size is about 0.5 mm, and they constitute 5-15 % of the pools. Chemical composition of the phlogopites are comparable to the phlogopites on collars, and they also have relatively high SiO_2 and low TiO_2 contents (Table 8). Composition of chrome diopsides are similar to the chrome diopsides of the average PTH nodules. The spinels in the pools are worm-shaped and fragmented, and have low Al_2O_3 and high TiO_2 contents compared to the spinels in the collars and in the other PTH nodules. The bulk chemical composition of the pools (Table 12) is an estimate based on modal proportions of the phases in the pools. Comparing the mineral association, some textural features and chemical composition of minerals of the collars and of the pools, the similarity between the two becomes apparent.

1. Both contain the assemblage: chrome diopside-spinel-phlogopite.
2. Some phlogopites are strained and deformed in both the collars and the pools.
3. The chemical composition of phlogopites in both occurrences are very similar (Table 8), and the chemistry of spinels although somewhat different in the collars, is still closer to the composition of spinels in the pools than spinels outside the pools (Table 11).

TABLE 12

ESTIMATED BULK COMPOSITION OF ROCKS

	Pool 1	2	3	4	5
SiO_2	43.73	47.00	42.08	44.05	47.58
TiO_2	0.26	0.25	0.29	0.26	0.17
Al_2O_3	8.31	7.70	9.87	10.24	7.20
Cr_2O_3	4.64	1.92	4.26	1.43	2.05
FeO	3.64	2.67	3.38	2.81	2.70
MgO	21.79	21.56	23.56	23.99	21.07
Na_2O	0.92	1.35	0.53	0.53	1.32
K_2O	5.74	2.56	7.36	7.65	4.78
CaO	6.66	8.57	3.81	3.81	9.52

There are three major differences between the collars and the pools:

a) the absence of garnet in the pools

b) the smaller and fewer phlogopites in the collars

c) the euhedral shapes of spinel in collars vs. the worm-shaped spinels in the pools.

These three differences may be explained by the following.

a) Supporting evidence that the pools originally contained garnets.

1. Spherical shape of pools resemble the average shape and size of garnets in other PTH nodules.
2. PTH-204 contains fragments of garnet in centre of a well-formed pool.
3. The orthopyroxenes of PTH-516 and PTH-108 were classified by the method of Dawson and Stephens, and they belong to the garnet lherzolite assemblage. Therefore garnet must have originally been part of the assemblage.
4. Mass balance calculations of the pools (Table 12) show high Al_2O_3 content, suggesting the original presence of garnets. It appears then, that the pools and collars of the subset nodules are related, but the pools are just more advanced collars.

The ultramafic nodules of Pipe 200 are believed to be samples of the upper mantle (Carswell *et al.* 1979). The subset nodules differ from the rest of the rocks by the presence of phlogopite-rich pools or by collars on garnets. As phlogopites represent a hydrous phase, the question arises, when and how was the fluid responsible for their formation incorporated into the ultramafic nodules. This thesis will discuss five possibilities that may be considered in the development of the pools and the formation of the phlogopites.

1. Primary metasomatism (Harte and Gurney, unpublished). A metasomatic event took place in the upper mantle, prior to the development of the kimberlite, and phlogopites formed as the result of this metasomatism.
2. Secondary metasomatism (Harte and Gurney, unpublished). Metasomatising fluid originated from the host kimberlite, and phlogopites were formed en route to the surface.
3. Metamorphism, involving the reaction ol+ gnt → 2 px + sp ± symplectite.
4. Phlogopite-rich pools represent droplets of magma trapped in the restite after a partial melting event. Recrystallization of these droplets took place prior to the incorporation of the nodules into the kimberlite.
5. Phlogopite-rich pools are the result of more than one event, and more than one single process. Since phlogopites are invariably associated with spinels and chrome diopsides, the mechanism(s) should be found to account for this mineral association.

1, 2: The Effects of Primary and Secondary Metasomatism on Peridotite Nodules (Harte and Gurney, unpublished)

Most inclusions in kimberlites show evidence of fluid penetration. The fluid is usually responsible for introducing new elements into the pre-existing rocks, resulting in the formation of new minerals. It can also change the pre-existing mineral chemistry in two ways (Gurney and Harte, unpublished): a) by diffusion metasomatism, which is responsible for the modification of mineral chemistry, and the formation of new minerals; b) by infiltration metasomatism that leads to the formation of new minerals. The latter process is considered to be the more important one, and responsible for the varied mineralogy of the kimberlite inclusions.

Two types of infiltration metasomatism can be distinguished (Gurney and Harte); a) primary and b) secondary. The primary metasomatic event occurs within the upper mantle, prior to the incorporation of nodules into the kimberlite. Minerals formed as the result of this metasomatism, are: phlogopites, potassic-rich richterites, rutile, ilmenite, Ba-Zn rich opaque minerals, and carbonate. The most widespread minerals that are formed from primary metasomatism are the phlogopites. These phlogopites are called primary, but only in the sense that they were the result of primary metasomatism.

<u>Secondary</u> metasomatism may take place during the incorporation of rocks into the kimberlite. It is an event associated with the upward movement of the kimberlitic magma. In this case, the phlogopites are associated with kelyphytes and serpentine. There are important petrographic and chemical differences between primary and secondary phlogopites. The textural differences between the two are, that primary phlogopites occur in isolated, coarse flakes or aggregates and they are in textural equilibrium with the adjacent minerals. The secondary phlogopites are associated with the alteration of garnets and kelyphytes. According to Boyd and Nixon (1976), deformation of phlogopites indicate that they were formed prior to their inclusion into the kimberlite.

In rock 26-34 the effects of kimberlite fluid interaction can be seen. Grain sizes in this peridotite nodule are 0.5-7.0 mm and the rock is composed of predominantly olivine and enstatite. Four large garnets (2-3 mm) are present with narrow kelyphytic rims, and very small euhedral spinels. Olivines are strained, displaying undulose extinction. A small degree of recrystallization is apparent at the contact with the kimberlite. Some 'spilling over' of the kimberlitic fluid is apparent. A serpentine vein crosscuts all the minerals near the contact.

Extensive alteration is absent in the rock at a distance of more than 5-6 mm from the contact. While the kimberlitic matrix contains a number of small (1 mm) phlogopites, they are absent from the nodule. It is apparent that the matrix of the kimberlite is rich in K_2O and TiO_2. Why have these elements not enriched the nodule? Although kelyphytic rims on garnets are indicative of the unstable position of garnets in sample 26-34, this instability failed to produce chrome diopside and phlogopite collars around the kelyphytes. It is evident from the presence of veinlets between garnets and kimberlite, that the alteration of garnets to kelyphyte are the result of metasomatic fluid migration to the nodule from the kimberlite. The strained olivines are cross-cut by these veins, suggesting that straining, deformation took place prior to the incorporation of the nodule into the kimberlite. Metasomatism and assimilation with the kimberlite resulted in only a limited amount of kelyphytization and serpentinization.

If secondary metasomatism failed to produce pools and collars on garnets in sample 26-34, then perhaps the presence of a migrating, metasomatising fluid is not sufficient to produce those textures at low temperatures and pressures.

3. Effects of Metamorphism

Metamorphic reactions may produce the mineral assemblage, chrome diopside + spinel, possibly with symplectic texture. The reaction ol + gnt → 2 px + spinel could therefore form collars on garnets. This process may be accompanied by the upward movement of the peridotite mass (upwelling). Mineral aggregates formed this way would be finer grained than the rest of the rocks.

4. Effects of Crystallization of Trapped Liquid

Crystallization of a droplet of liquid, left over from a partial melting event may result in mineral aggregates that occupy a more or less spherical area. The bulk composition of that 'pool' would be close to the composition of basalt. Table 12 shows the estimated bulk composition of the pools in the PTH subset nodules. It is apparent from the table that pool composition substantially differs from the composition of basalts.

A SUMMARY OF THE EVIDENCE FOR THE ORIGIN OF THE POOLS AND AN 'INTEGRATED MODEL' FOR THE SEQUENCE OF EVENTS IN THE DEVELOPMENT OF THE POOLS

Figure 7 lists four possible models (based on evidence) for the origin of the collars and pools. To reconstruct the sequence of events in the development of the collars and pools, the following questions should be answered:

What is the evidence for depletion?

High Mg/(Mg + Fe), High Cr/(Cr + Al), Low CaO, Na_2O } for the whole rock composition

High Cr/(Cr + Al) for Cpx

High Cr/(Cr + Al) for Garnet

When did the depletion take place relative to pool formation?

Prior to the formation of the pools and collars. The grain sizes of these mineral aggregates are smaller than the average grain sizes in the rocks. Phlogopites are present in the pools and collars, but absent from the rest of the rocks. Phlogopites constitute the hydrous phase of the pools. Then if they were present prior to depletion, they would have been the first minerals to disappear during partial melting.

FIGURE 7

MODELS FOR THE ORIGIN OF THE COLLARS AND POOLS

Collars and Kelyphtye	1 PRIMARY METASOMATISM	2 SECONDARY METASOMATISM	3 METAMORPHIC PROCESSES	4 Xlzn of TRAPPED LIQUID
Mineral Association	Phlogopites may be formed by both processes		Collars of 2px ± sp can be produce of metamorphic reactions during Preduction of a garnet lherzolite	
Texture	Strained phlogopites formed before inclusion into kimberlite (Boyd and Nixon)	fine-grained kelyphyte is probably late secondary	recrystallization triple junctions coarsely crystalline	
Mineral Chemistry	Phlogopites of this composition are tpyical of primary metasomatism (Carswell)			
POOLS				
Mineral Association	Phlogopites may be formed by both processes		assemblage 2 px ± sp ± symplectite are product of metamorphic reactions	
Texture	Large grains → slow crystallization are atypical of kimberlites, phlogopites must have been present prior to inclusion ——— Deformation takes place prior to inclusion		recrystallization	
Mineral Chemistry	Composition is typical of primary metasomatism (Carswell)			mass balance of pools do not have the chemical composition of basalts

What is the evidence for metamorphic recrystallization?

Mineral association spinel + chrome diopside forming at the expense of garnet.

The collars on garnets (textural).

The small grain sizes of minerals in the pools and in the collars, relative to the average grain sizes in the rest of the rocks.

When did metamorphism take place relative to these events?

After depletion, as the partial melting event probably would have destroyed the small aggregates of clinopyroxenes and sympletic spinels.

What is the evidence for metasomatism?

Presence of phlogopites in collars and pools.

Large amounts of K and H_2O are probably only introduced into this mineral assemblage by metasomatism.

When did metasomatism take place?

Prior to incorporation into the kimberlite, as phlogopites have primary composition and some are strained and deformed.

Compiling all evidences into an "Integrated Model" (Fig. 8), it is now possible to reconstruct the proper sequence of events which took place during the formation of the collars and pools.

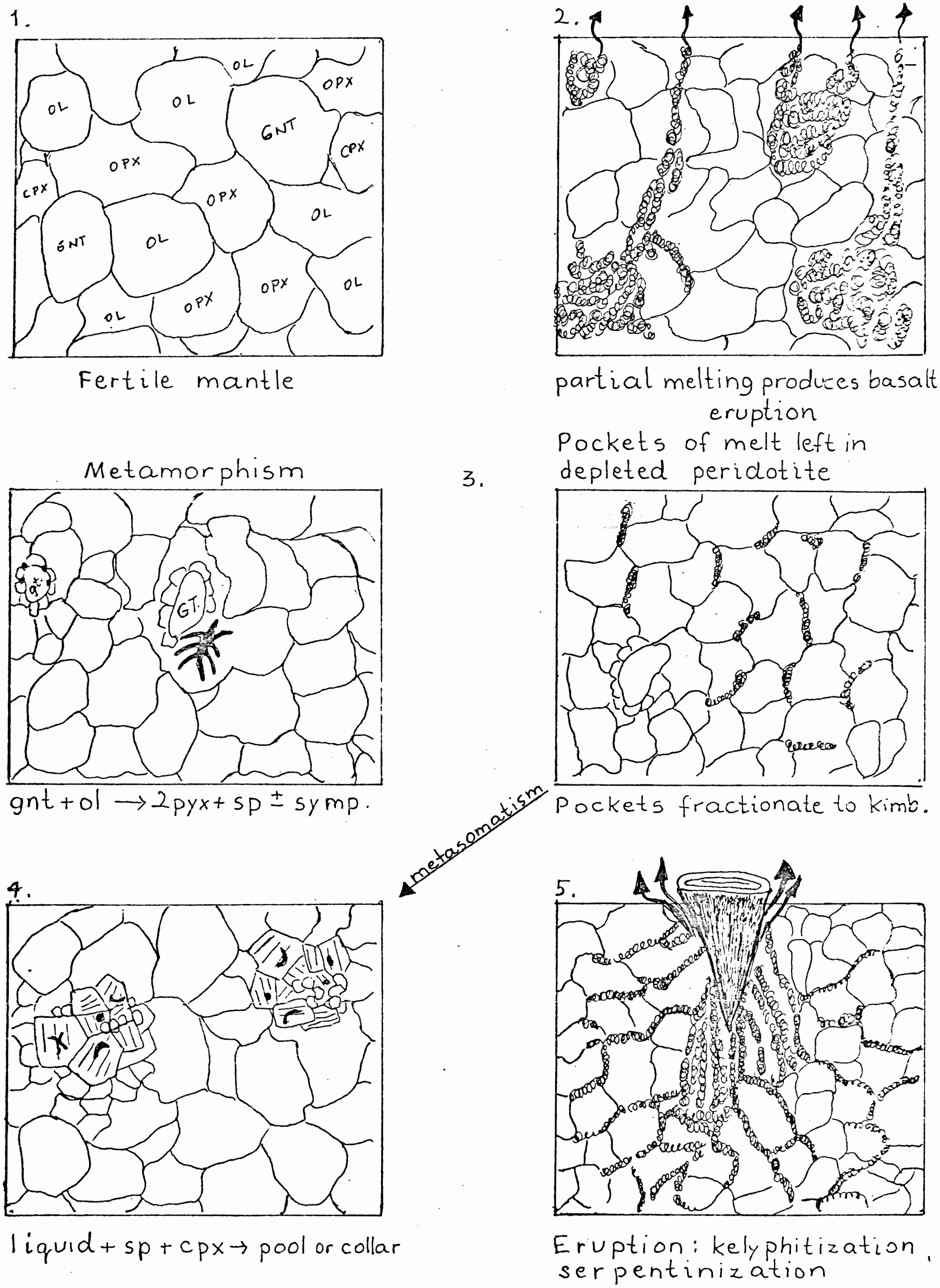
FIGURE 8

THE INTEGRATED MODEL OF THE COLLARS AND POOLS

START	PARTIAL MELTING	METAMORPHISM	PRIMARY MANTLE METASOMATISM	INCLUSION INTO KIMBERLITE ERUPTION OF KIMBERLITE	END
	DEPLETION (Carswell et al.) Whole rock analysis	Garnet has collars of cpx + euhedral spinel. Reaction: Gnt + ol → 2 px + sp	Primary phlogopites includes in collars, some are strained, deformed. Number of phlogopites are relatively few and grain sizes smaller than in pools	Kelyphytization of garnets, serpentinization in rock	Altered, depelted collared kelyphytized peridotite
PRISTINE FERTILE GARNET LHERZOLITE	High Mg/(Mg+Fe) High Cr/(Cr+Al) Low CaO, Na_2O	↑ DEPTH DECREASING	less ↑ FLUID AVAILABLE ↓ more		
	Cpx: High Cr/(Cr+Al) Garnet: High Cr/Cr+Al	Mineral association contains small grains of chrome diopside and worm-shaped fragmented spinel. Reaction may be: Gnt + ol → 2px + sp (symplectite)	Primary, large phlogopites are part of the assemblage. Some are strained, deformed	Serpentinization is evident	Altered, depleted, pooled peridotite

Figure 9

Sequence of events in the development of the Pools



Start with fertile garnet lherzolite.

1. Partial melting → depleted garnet lherzolite.
2. Metamorphism during slow upward movement of the peridotite mass.
3. Primary metasomatism to varying degrees.
4. Inclusion into kimberlite.
5. Eruption of kimberlite.

End with collars or fully formed pools.

Figure 9 is a schematic diagram depicting the above sequence of events.

CONCLUSION

From the foregoing evidence it is possible to reconstruct the history of the pools and of the collars on garnets with some degree of confidence. According to the "Models for the Origin of the Collars and Pools" one single process cannot account for their presence in the PTH subset nodules. They were probably formed by a combination of processes (a) metamorphism and (b) primary metasomatism. The first event involved the reaction olivine + garnet → opx + cpx + spinel (symplectite). This reaction may have been triggered by the upward diapiric movement of the peridotite mass. The second event, primary metasomatism, involved the introduction of K + H_2O and the crystallization of phlogopites. As phlogopites are relatively coarse-grained in the pools, they must have had a slow crystallization history.

After they were formed, they suffered strain and deformation.

The subset nodules with the fully formed pools and collars or garnets were then incorporated into the fast-moving kimberlite. Where garnets still remained, they were kelyphytized. Extensive serpentinization took place at near the end of the eruption.

Summarizing the evidence then, the pools of PTH-516, PTH-108, the semi-formed pools of PTH-204 and the collars on garnets of PTH-58 were formed prior to their incorporation into the kimberlite. The differences in the degree of alteration (from garnet to pool) are probably due to the differences in their depth of origin, and to the availability of metasomatizing fluid. It appears that large quantities of metasomatising fluid were not involved in the above reactions, but the fluid was restricted to certain sites. In accordance with the abundances of phlogopites in the pools relative to the number of phlogopites in the collars on garnets, it may be argued that the metamorphic reaction that produced the collars may never have reached completion without the presence of metasomatising fluid. The reaction ol + gnt $\rightarrow$ 2 px + sp formed a protective rim of reaction products and only the metasomatising fluid was able to break down the remaining garnet. Where wormy symplectic spinels are present in the pools, the breakdown of garnet probably took place prior to metasomatism.

Further petrological work is required to test for the validity of the above hypothesis. If the relationships hold true, we should find the mineral association of the pools present in other depleted garnet and/or spinel lherzolites as well. Frey and Prinz (1978) analysed ultramafic inclusions from basanites of San Carlos, Arizona, and found one type of nodule 'spinel lherzolite', that appears to bear some resemblance to the texture and mineral assemblage of the subset nodules of Pipe 200. Their spinel lherzolites contain a relative abundance of phlogopites, amoeboid spinel, and clinopyroxenes with spongy, porous rims.

Further study on the Al_2O_3 contents of ortho- and clinopyroxenes may be useful. According to Ito and Kennedy (1967), in the system of CaO-MgO-Al_2O_3-SiO_2, the Al_2O_3 content of diopside coexisting with forsterite and spinel decreases with increasing pressure. They observed that the Al_2O_3 content of enstatite solid solution decreases with increasing pressure when coexisting with pyrope. Opx of PTH-108 have a low 0.59% Al_2O_3 content in comparison to the average PTH nodules (1.10%). Similarly, diopsides have a lower than average Al_2O_3 content in the same rock (1.64% vs. 3.42% of PTH). The orthopyroxenes and clinopyroxenes in the spinel lherzolites of Frey and Prinz also have lower than average Al_2O_3 percentage. A further analysis of pyroxenes associated with pools of phlogopites-chrome diopsides-spinels could be the next step in investigating the depth of origin of other rocks containing pools similar to the pools of the PTH nodules.

ACKNOWLEDGEMENTS

I am very grateful to Dr. D.B. Clarke for his support and encouragement while the writing of this thesis was in progress. Only his help and valuable advice made this project possible.

I would also like to thank Dr. G.K. Muecke for his valuable suggestions, and Bob MacKay for his much appreciated help with the microprobe analysis. Special thanks to D. A. Carswell, D. B. Clarke, R. H. Mitchell, J. Andrews, M. J. O'Hara, B. Harte for the samples used in this project.

REFERENCES

Basu, A. R. And MacGregor, I.D. Chromite spinels from ultramafic xenoliths. Geochim. Cosmochim. Acta, 1975, vol. 39.

Boullier, A.M. and Nicolas, A. Classification of textures and fabrics of peridotite xenoliths from South African kimberlites. IN Lesotho Kimberlites, edited by P. H. Nixon, 1973.

Carswell, D.A. Primary and secondary phlogopites and clinopyroxenes in garnet lherzolite xenoliths. Phys. Chem. Earth 9, 431-454, 1975.

Carswell, D.A., Clarke, D.B., Mitchell, R.H. The petrology and geochemistry of ultramafic nodules from Pipe 200, Northern Lesotho. Proceedings of the Second International Kimberlite Conference, vol. 2, 1979.

Cawthorn, R. G. and Collerson, K.D. The recalculation of pyroxene end-member parameters and the estimation of ferrous and ferric iron content from electron microprobe analyses. Am. Min., v. 59, p. 1203, 1974.

Cox, R. G. and Jamieson, B.G. The olivine-rich lavas of Nuanetsi: a study of polybaric magmatic evolution. Journal of Petrol. vol. 15, 1974.

Dawson, J. B. Advances in kimberlite geology. Earth Sci. Rev., 1971.

Dawson, J.B. and Stephens, W.E. Statistical classification of garnets from kimberlite and associated xenoliths. J. Geol., 83, 589-607, 1975.

Frey, F.A. and Green, D.H. The mineralogy, geochemistry and origin of lherzolite inclusions in Victorian basanites. Geochim. Cosmochim. Acta, 38, 1974.

Frey, F.A. and Prinz, M. Ultramafic inclusions from San Carlos, Arizona: Petrologic and geochemical data bearing on their petrogenesis. Earth and Planetary Science Letters, 38, 1978.

Gurney, J.J. and Harte, B. Chemical variations in upper mantle nodules from Southern African Kimberlites (unpublished).

Harte, B., Cox, K.G., Gurney, J.J. Petrography and geological history of upper mantle xenoliths from the Matsokv Kimberlite Pipe. Phys. Chem. Earth, 9, 1975.

Ito, K. and Kennedy, G.C. Melting and phase relations in a natural peridotite to 40 kilobars. Amer. Journal of Science, 265, 1967.

Kresten, P. and Dempster, A.N. The geology of Pipe 200 and the Malibamatso Dyke Swarm. Lesotho Kimberlites, Lesotho National Development Corp., 1973.

MacGregor, I.D. Stability fields of spinel and garnet peridotites in the synthetic system MgO-CaO-Al_2O_3-SiO_2.

MacGregor, I.D. The system MgO-Al_2O_3-SiO_2: solubility of Al_2O_3 in enstatite for spinel and garnet peridotite compositions. American Mineralogist, 59, 1974.

MacGregor, I.D. The effect of CaO, Cr_2O_3, Fe_2O_3 and Al_2O_3 on spinel and garnet peridotites. Phys. Earth Planet. Interiors, 3, 1970.

Nixon, P.H., Boyd, F.R., Boullier, A. The evidence of kimberlite and its inclusions on the constitution of the outer part of the Earth. Lesotho Kimberlites, Lesotho National Development Corporation, 1973.

Stephens, W.E.and Dawson, J.B. Statistical comparison between pyroxenes from kimberlites and their associated xenoliths (unpublished).

Wood, B.J. The solubility of alumina in orthopyroxene co-existing with garnet. Contr. Mineral. and Petrol., 46, 1974.

Wood, B.J. and Banno, S. Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. Contr. Mineral. Petrol. 42, 1973.

Wells, P.R.A. Pyroxene thermometry in simple and complex systems. Contr. Mineral. Petrol. 62, 1977.

APPENDIX "A"

PETROLOGICAL DESCRIPTION OF ROCKS

Slide 404

Olivine = 60%

Orthopyroxene = 20%

Garnet = 10%

Spinel + chrome diopside = 10%

Two types of chrome diopsides are present in the slide; (a) large euhedral 'blebs' associated with partially kelyphytized garnets, (b) collars of small chrome diopsides on kelyphytic rims of garnets. Minor phlogopites are present, but in lesser amount than diopsides. Serrated, spongy rims on most diopsides are absent. Notable feature on this slide is, the minute olivine grains occurring in veins and between grain boundaries. Polygonization and recrystallization is apparent throughout the slide. Orthopyroxenes are strained. Two types of kelyphytized garnets are present (a) one that consists of only kelyphyte and spinel, (b) garnet only partially kelyphytized and it is associated with chrome diopside and spinel. Although spinels are present in both cases, phlogopites and chrome diopsides are not. Metasomatising affect on this rock is similar to

26-34, where dark, opaque veins cross-cuts all the minerals. Grain sizes of opx and olivines range between 7 mm to fraction of 1 mm. Notable difference between the spinels of 404 and other rocks is, the high 46.4 Al_2O_3 and low 18.7% Cr_2O_3 content.

Slide 516

Orthopyroxene = 50%

Olivine = 25%

Chrome diopside + phlogopite + spinel = 25%

This slide contains two types of pools, (a) 'common' phlogopite-chrome diopside-spinel pools, and the (b) chrome diopside-spinel-minor phlogopites pool (may be due to different sectioning of the rock). Both pools are elongated and have a mosaic texture. The only apparent difference between the two is the amount of phlogopites present, and spinel grain-sizes are much larger in the chrome diopside 'pools'. The degree of recrystallization in this rock is limited, and restricted mainly to the vicinity of the pools. The average grain-size of orthopyroxenes range between 2-3.0 mm. Some pools are elongated, while others are spherical. Recrystallization of olivines can be seen adjacent to elongated pools, while spherical ones are surrounded mainly by large orthopyroxenes. Pools in this slide contain strained phlogopites and 'wormy-spinels'.

Slide 58

Orthopyroxene = 50%

Olivine = 20%

Garnet + chrome diopside + spinel + phlogopite = 30%

The characteristic feature of this rock is the elongation of grains in one direction. The general appearance of minerals suggests straining and flattening. Undulose extinction is common to both large and smaller grains. The small grains are located between grain boundaries. They are predominantly olivines, but some small grains of orthopyroxenes are present as well. Grain sizes range between 0.5-7.0 mm. Kelyphytized garnets are numerous in the slide, and most kelyphytes are rimmed with collars of chrome diopsides and phlogopites. Phlogopites are extensively strained and have undulose extinction. Spinels are mainly euhedral, and some grains are poikilitically enclosed by phlogopites. Phlogopites constitute only 20-30% of the collars on kelyphytized garnets, and chrome diopsides predominate. A number of spinels have a 'rounded' appearance, due to the minute aggregates of phlogopites clustering on their margins.

Slide 108

Olivine = 50%

Orthopyroxene = 30%

Chrome diopside + spinel + phlogopite = 20%

This is an extensively metasomatized rock. Three generations of olivines are present; 2-5.0 mm, 0.5-1.5 mm, and 0.5 mm. Polygonization and recrystallization are apparent features, resulting in a second generation of olivines. The smaller crystals are located predominantly between grain boundaries in veins. The three 'generations' of olivines are probably the result of the continuous cycle of Harte et al. (1976), where they form by strain-deformation, recrystallization and grain growth. Orthopyroxenes range in size between 0.5-2.5 mm. Some are recrystallized and located between grain boundaries. Large grains are strained. Chrome diopsides occur in pools, or as individual aggregates. Phlogopites constitute a large percentage of the pools, spinels are less common than in rock 516. Some pools consist of two different sizes of phlogopites, (a) large, well-shaped grains of 0.5-1.0 mm, (b) tiny grains in veins, associated with small olivines. The chemical composition of both types of phlogopites are similar.

Slide 26-34

This slide is not part of the pipe 200 nodules. It contains both, a garnet lherzolite nodule and part of the enveloping kimberlite. The rock consists of 50% orthopyroxene, 40% olivine and 10% garnet. Orthopyroxene grains are extensively strained, displaying undulose extinction. Their size range is between 5-6.0 mm. Olivine crystals are strained, polygonized and recrystallized. The extent of recrystallization is limited to the vicinity of the kimberlite contact. Metasomatism is more extensive at the contact, and a 'spilling-over' of the kimberlitic fluid is apparent up to 4-5.0 mm from the kimberlite contact. The garnets are moderately kelyphytized with a narrow rim. Chrome diopsides and phlogopites are absent from the nodule. The extent of metasomatism is much smaller than in numbers 516, 404, 204 and 58. The kimberlite matrix contains a number of very small phlogopites (< 1 mm), and their chemical composition is similar to Carswell's secondary phlogopites. The nodule is extensively serpentinized.

APPENDIX "B"

PLATES

PLATE 1. Symplectic intergrowth of spinel with chrome diopsides. XN.

Magnification: 80

PLATE 2. 'Wormy' spinel in 'pool'. PPL.

Magnification: 80

1.

2.

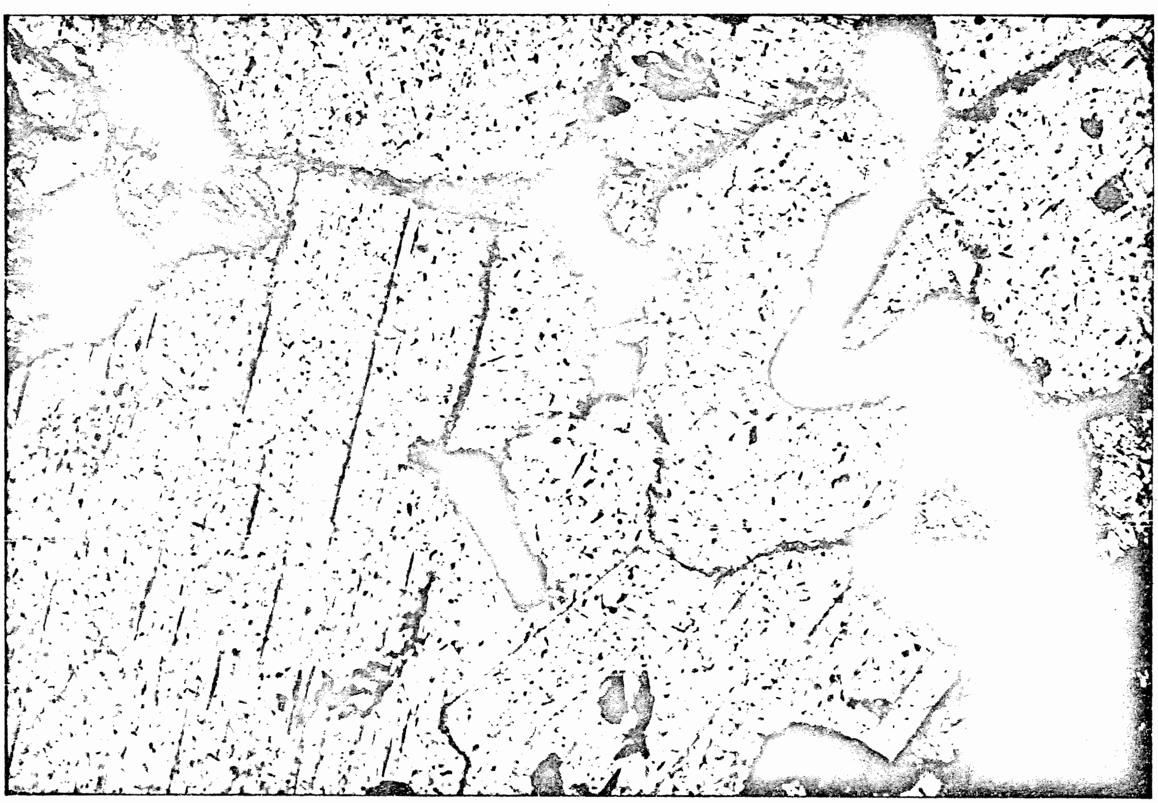


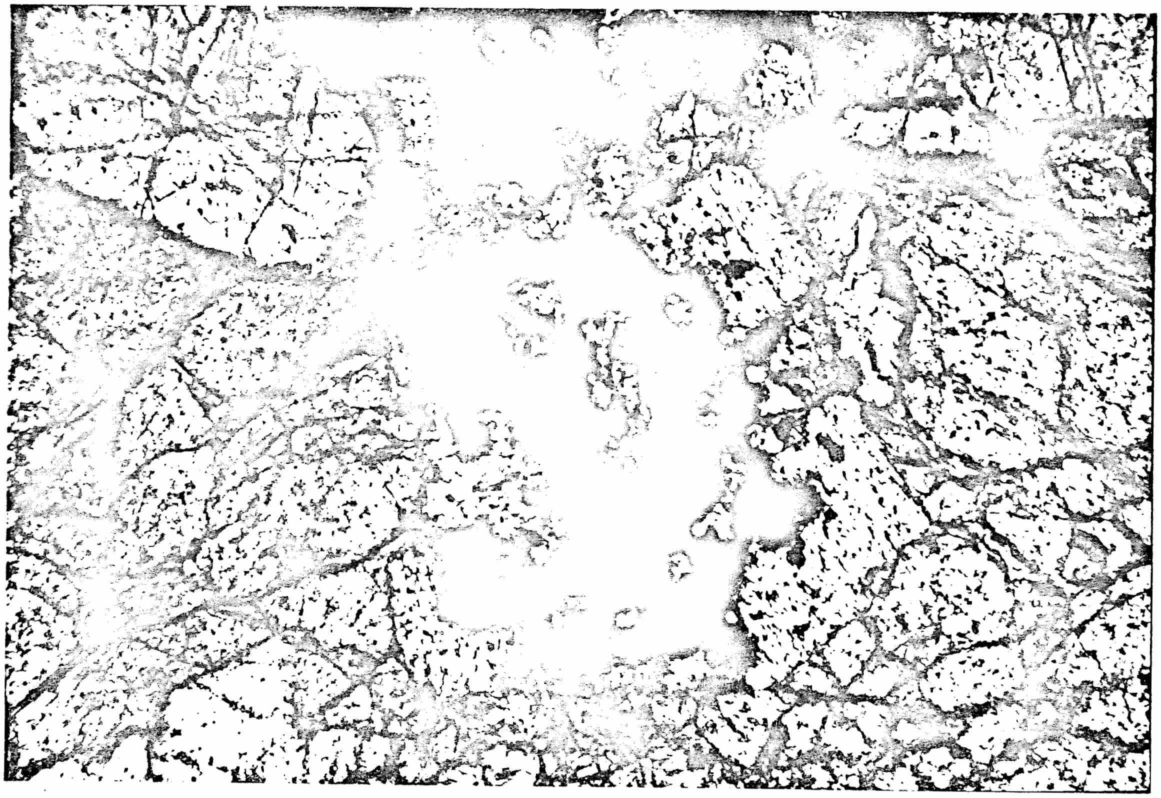
PLATE 3. Kelyphytized garnet with collar of chrome diopside and phlogopite. PPL.
Magnification: 80

3.

PLATE 4. 'Pool' of phlogopites-chrome diopsides and spinel, with garnet in centre - Kelyphytized. PPL. Magnetification: 20

PLATE 5. Same with XN.

4.



5.

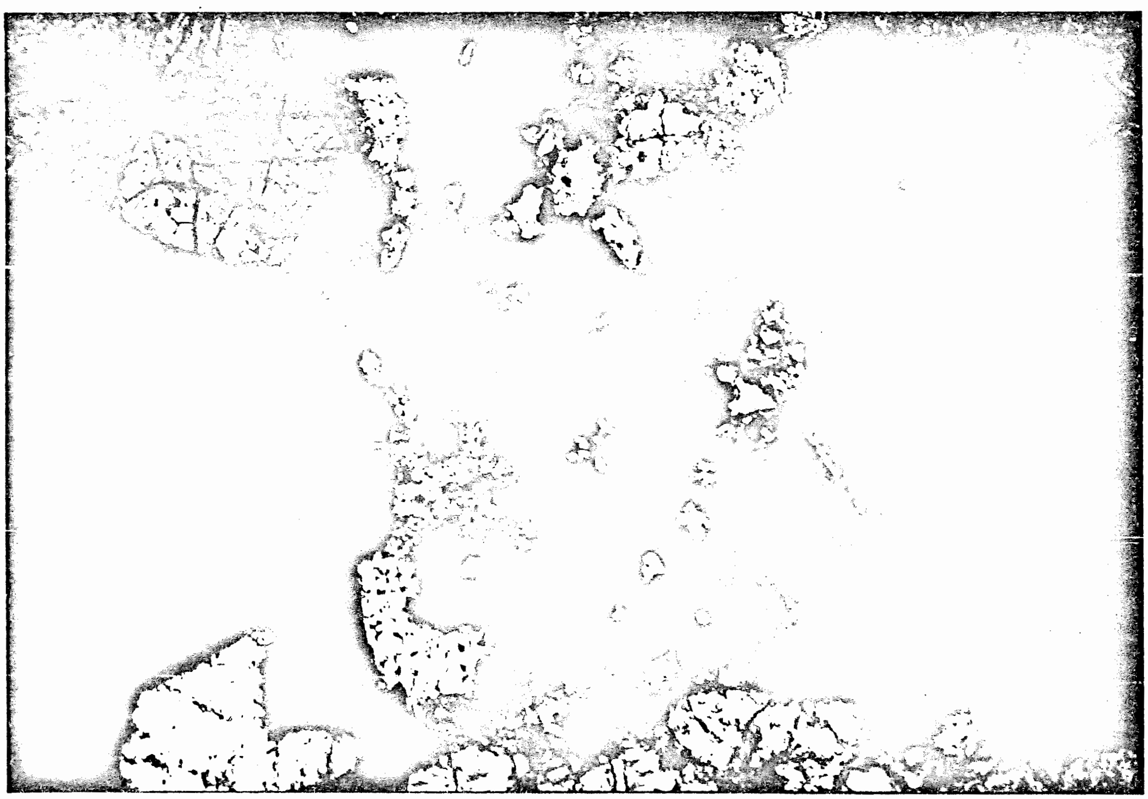


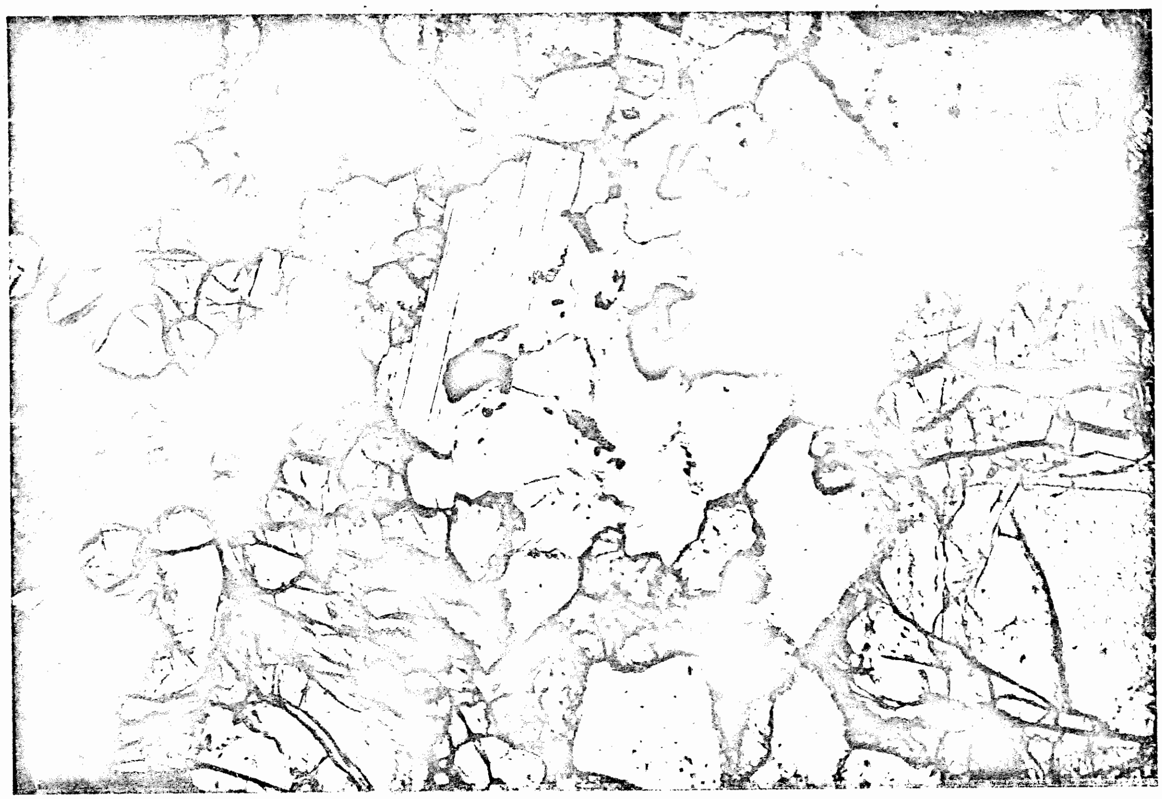
PLATE 6. A typical fully formed 'pool' of phlogopites-chrome diopsides-spinel. PPL.

Magnification: 20.

PLATE 7. Same with XN

Magnification: 20

6.



7.

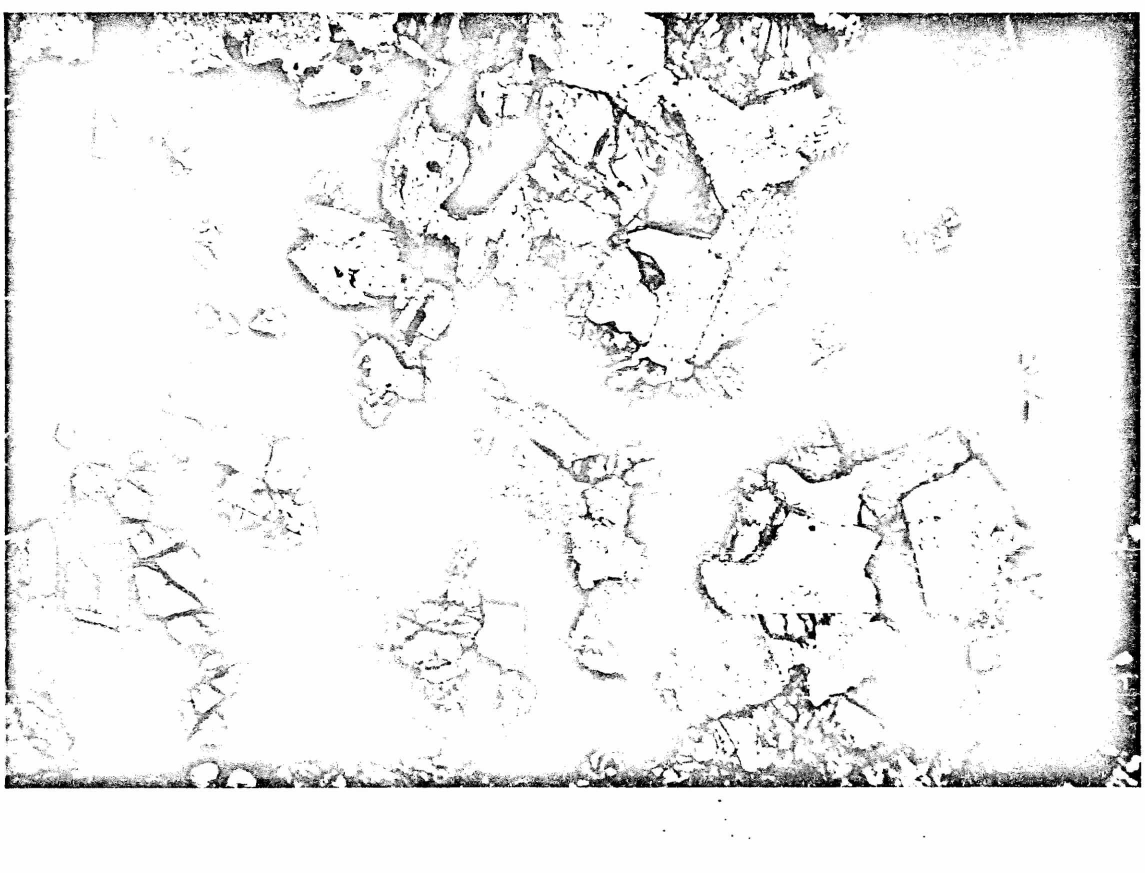


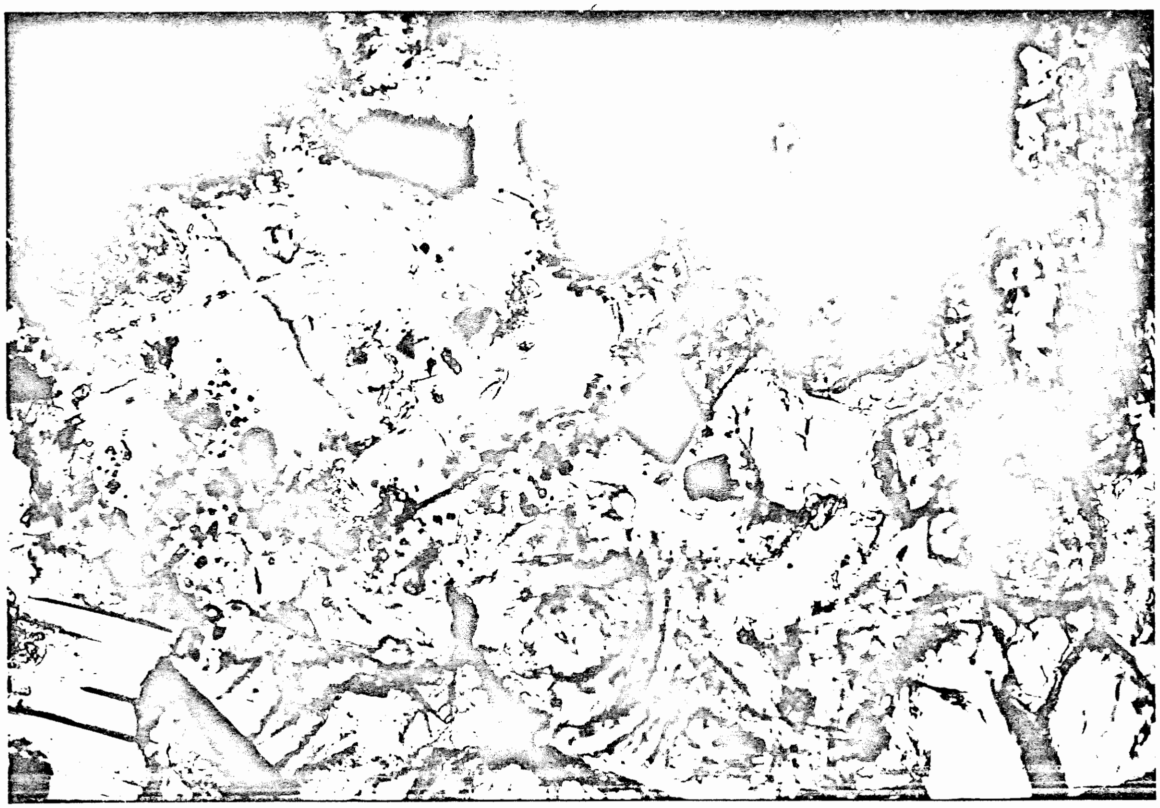
PLATE 8. Spinels: Euhedral spinel; 'Corroded' spinel in phlogopite. PPL.

Magnification: 80

PLATE 9. 'Wormy' spinel. PPL.

Magnification: 80

8.



9.

Approximate time spent on thesis:

Microprobe analysis	50 hours
Research Microscope Work Writing	3 months or 550 hours
TOTAL	600 hours