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**Composition of apatite from the Oka Carbonatite Complex,
Quebec: implications for melt evolution**

ANN C. TIMMERMANS

2003

Composition of apatite from the Oka Carbonatite, Quebec: implications for melt evolution

By

Ann C. Timmermans

A thesis submitted to

the Faculty of Graduate Studies and Research

in partial fulfillment of

the requirement for the degree of

Master of Science

Department of Earth Sciences, Carleton University

and

Ottawa-Carleton Geoscience Centre

Ottawa, Ontario

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**Composition of apatite from the Oka Carbonatite Complex,
Quebec: implications for melt evolution**

Submitted by Ann C. Timmermans, B.Sc.
In partial fulfillment of the requirement for
the degree of Master of Science

Thesis Supervisor

Chairman, Department of Earth Sciences

Carleton University

2003

ABSTRACT

Apatite is a common accessory mineral in igneous rocks that is sensitive to minor changes in rare earth element (REE) concentrations. Hydroxylapatite and less common fluorapatite, in eight carbonatite and four silicate rocks, were confirmed by electron microprobe analyses in samples from the Oka Carbonatite Complex, Quebec. These minerals contained significant amounts of Ca, P, Sr, La, Ce, Si, OH and F, as well as less important amounts of Na, S and Cl. Barium, Pr, Nd, Sm and HREE were below the detection limit, and C could not be detected with the available instrumentation. In the Oka apatite, the cations Na^+ , Sr^{2+} , La^{3+} and Ce^{3+} partly replaced Ca^{2+} . The cations Si^{4+} , S^{6+} and possibly C^{4+} , partly replaced P^{5+} . The anions F^- and Cl^- partly replaced $(\text{OH})^-$.

The REEs are incorporated into the apatite crystal structure primarily by the coupled substitution $\text{Ca}^{2+} + \text{P}^{5+} \leftrightarrow \text{REE}^{3+} + \text{Si}^{4+}$. Many authors have shown that the LREE abundances increase from earlier to later stages of the magmatic formation of carbonatite and associated rocks, which is reflected in apatite. This relationship is best illustrated when apatite data for La+Ce+Si are plotted against Ca+P in atoms per formula unit (apfu). From this plot three observations can be made: 1) both carbonatite and silicate rocks contain variable abundances of LREE, 2) the data for both the carbonatite and silicate rocks produce negative correlations along a similar slope, 3) apatite from particular carbonatite and silicate rocks overlap in their La+Ce+Si and Ca+P abundances. These observations lead to the following progression of rock types included in this study (from low La+Ce+Si to high La+Ce+Si abundance): for carbonatite rocks: medium+coarse-grained carbonatite $\rightarrow$ pegmatitic + monticellite carbonatite $\rightarrow$ layered carbonatite $\rightarrow$ perovskite carbonatite $\rightarrow$ niocalite carbonatite. For the silicate rock types: calcite ijolite $\rightarrow$ melanite ijolite $\rightarrow$ apatite okaite+ nepheline okaite.

Electron backscattered images of apatite from Oka shows oscillatory and/or sector zonation not seen in transmitted light. Electron microprobe analysis has revealed that the zones within the apatite vary in LREE+Si content. The origins of the zones in the Oka apatite remain unclear. However, textural evidence within the Oka rocks supports a convecting magma chamber or a pulsing magma source. Intrinsic forces contributing to the development of the apatite zonation remain another possibility.

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CHAPTER 1

INTRODUCTION

Hydroxylapatite and fluorapatite are common accessory minerals in igneous rocks. Known for its high abundance of trace and rare earth elements (REE), apatite is of petrogenetic interest to many geoscientists. It has been shown that the ratio of certain REE differs from rock type to rock type within a carbonatite suite (Kapustin, 1966; Balashov and Sharas'kin, 1966). These variations in REE abundances have been used to propose a model for the magmatic evolution of a carbonatite system where a distinct REE assemblage characterizes each stage. Eby (1975) was one of the first authors to develop a petrogenetic model for the Oka Carbonatite Complex by analyzing trace and REE in whole-rock, calcite, apatite and silicate minerals from several rock types.

The Oka Carbonatite Complex is located in the western part of the Monteregian Hills Province, Quebec (Gold, 1963, 1967; Gold *et al.*, 1986). The Oka Complex is composed of carbonatite and undersaturated ultra alkaline silicate rock types. Fairbairn *et al.* (1963) were the first to confirm the age of the Oka Complex to be Cretaceous. More recently, Wen (1985) obtained a well-defined Rb-Sr isochron based on biotite data from both carbonatite and silicate rock types that correspond to a date of 109 ± 2 Ma. This is younger than the apatite fission track studies (Shafiqullah *et al.*, 1970; Eby, 1984b; Gold *et al.*, 1986) that reveal a clustering of ages for various rock types over a 12 million year time span, grouped at approximately 120 Ma. With several carbonatite and silicate intrusive episodes, the Oka Carbonatite Complex harbours many questions about its chemistry and origin.

With the use of more advanced imaging techniques, it has been discovered that many of the rock-forming minerals (including apatite) from Oka are zoned (Hogarth, 1989; Shore and Fowler, 1996). Figures 1.1 and 1.2 are examples of backscattered images of Oka apatite. There are two types of zoning found in Oka apatite: oscillatory zoning (outlines former growth surfaces, Shore and Fowler, 1996) and sector zoning (compositional differences between time-equivalent but symmetry-nonequivalent growth sectors; Reeder *et al.*, 1989). Oscillatory zones may record changes in composition, redox state, temperature and pressure of the parent melt (Reeder *et al.*, 1989). The formation and preservation of oscillatory zonation, however, is still unresolved. Extrinsic mechanisms involve physical or chemical changes that are partially or wholly independent of local crystallization, such as magma differentiation (Shore and Fowler, 1996). Intrinsic mechanisms primarily associate crystal growth to a combination between rate of crystal growth and solute diffusion through the crystal-melt boundary layer (Shore and Fowler, 1996). With a high distribution coefficient (>1), the apatite mineral can preserve the REE information within each zone from its source rock up to relatively high temperatures ($>670^{\circ}\text{C}$). Zonation within Oka apatite has the potential of providing insights into the chemical and thermal history of its igneous system (Cherniak, 2000).

Although the zonation of apatite minerals from the Oka Carbonatite Complex has been noted in the literature (Girault, 1966; Hogarth, 1989; Shore and Fowler, 1996; Hornig-Kjarsgaard, 1997), there has been no comprehensive study of the difference in the major, trace and RE elements among the different zones. This thesis uses backscattered electron (BSE) images and electron microprobe analysis to evaluate the major and light REE within the different rock types as well as among the zones. This approach was

taken to help understand the relationship between the carbonatite and silicate rocks, the origin of the two types of zonation, and to evaluate whether it can be used to contribute to our understanding of the dynamics within a magma chamber.

Figure 1.1: SEM backscattered electron images of Oka apatite from carbonatite rocks. Photographs a) and b) show apatite (in thin section) from the niocalite carbonatite; c) and d) show apatite (in grain mount) from the layered carbonatite; e) and f) show apatite (in thin section) from monticellite carbonatite. The scale bar is located within each photograph.

Figure 1.2: SEM backscattered electron images of Oka apatite from silicate rocks. All photographs are taken of apatite in thin section. Photographs a) and b) apatite from an ijolite silicate rock; c) and d) apatite from apatite okaite; e) apatite from okaite, and f) shows apatite from melanite ijolite. The scale bar is located within each photograph.

CHAPTER 2

THE OKA CARBONATITE COMPLEX

The Oka Carbonatite Complex forms part of the Montereian Petrographic Province and lies approximately 180 km east of Ottawa, Ontario. The term Montereian Hills Province was first used in 1903 (Adams, 1903) to represent the erosional remnants of a series of alkaline and granitoid plutons that are preserved as prominent hills from Montreal eastward across the St. Lawrence Lowlands (Gold, 1966, 1967; Gold *et al.*, 1986). Recently the province was extended to include all lower Cretaceous dykes, sills, plugs, pipes and fissures of alkalic and carbonatitic affinity in the Ottawa and St. Lawrence lowlands, as well as parts of the Appalachians and Grenville provinces (Figure 2.1, Gold *et al.*, 1986; Hogarth *et al.*, 1988).

The rocks of the Montereian Igneous Province change in composition from west to east. Rocks in the west are Fe-rich and Si-poor whereas towards the east the Si content increases and Fe-content decreases (Gold *et al.*, 1986). The Oka Carbonatite Complex is located in the western end of the Montereian Hills and consists of outward dipping ring dykes and breccia pipes containing carbonate-rich and silica-undersaturated silicate rocks.

The Oka Complex is roughly oval and geologically divided into two ring structures. Oka's total areal extent is approximately 7.2 km by 2.4 km and the complex is composed of various rock types. The surface exposure of the complex is a series of

Figure 2.1: Map showing the localities of igneous rocks considered to be part of the Monteregian Igneous Province. The tectonic environment from west to east are the Grenville Province, the St. Lawrence lowlands and the Appalachian Orogenic Belt. The Oka Carbonatite Complex is located on the west side of the Monteregian area.

rolling hills reaching a maximum relief of 166 m above sea level in the northwest. The region was thoroughly mapped in the early 1960's. Agricultural practices over the complex contrast with vast hardwood vegetation in the surrounding quartzofeldspathic gneisses and anorthosites. Active urbanization on part of the complex has effectively covered many outcrops. Geophysical survey (magnetic and gravity) and drill cores were used to map the subsurface geology, and shallow seismic reflection surveys were conducted to map the shallow deposits (Gold *et al.*, 1967). These combined with deep trench drilling and topographic surveys contributed to the final geological map of the Oka Complex (Gold *et al.*, 1967; Figure 2.2).

The Oka Complex can be divided into three series (see Table 2.1, 2.2 and 2.3) each characterized by a distinct rock types. Each of the rock series, carbonatite, okaite and ijolite, are considered in this study.

The *carbonatite series* consists of at least eleven mineralogical types of carbonatite rocks that underlie about half of the surface area of the complex (see Table 2.1). Most are coarse-grained, layered and in places pegmatitic. Accessory minerals include apatite, sodian augite, phlogopite, nepheline, monticellite, melilite, pyrochlore, perovskite, niocalite, richterite, magnetite, pyrite and pyrrhotite (Gold, 1966, 1967; Gold *et al.*, 1986).

In the *okaite series* there are five members (Table 2.2), which are made up of mafic coarse-grained rocks that contain melilite and pyroxene, commonly with

Figure 2.2: Geological map of the Oka Carbonatite Complex, Quebec. Reproduced from Gold (1967). Samples were collected from the four locations indicated by the arrows.

accessory magnetite, apatite and perovskite. In general, the okaite series of rocks contain 40-90% melilite, 10-40% nepheline, as well as apatite, perovskite, magnetite and phlogopite (Gold, 1966, 1967; Gold *et al.*, 1986). It should be noted that in the literature the mineral hine is included in the modal mineralogy for many okaites from Oka. However, no hine was found in any of the samples analyzed during this study. Using the IUGS classification scheme, okaite would now be classified as a melilitolite. Samples from the nepheline okaite and apatite okaite from Husereau Hill were used in this study.

In the *ijolite series* the rocks are composed of mafic coarse-grained rocks that contain nepheline and diopside with accessory calcite, melanite and apatite. There are eight rock types within the ijolite series (see Table 2.3, Gold *et al.*, 1986). For the purpose of this study, calcite ijolite (from the St. Lawrence Mine) and melanite ijolite (from the Nature Centre) are evaluated.

From 2000 to 2002, this author visited the Oka Carbonatite Complex on five occasions for the purpose of in situ study and sample collection. Also used in this study were samples from Jianping Wen (collected in 1985) and Dr. K. Bell (collected in 1997) of Carleton University. There are four areas within the Oka Carbonatite Complex from which samples were collected: Area 1 (A1) Husereau Hill, (A2) Bond Zone, (A3) St. Lawrence Mine, and (A4) the Nature Centre. Figure 2.3 A to E are photographs of some of these areas, and descriptions of the locations are summarized below.

Table 2.1. Carbonatite Series - Eleven groups of carbonatite rocks have been identified within the Oka Carbonatite Complex, Quebec (Gold, 1972)

1. Flow-layered calcite rock with accessory pyroxene, phlogopite and magnetite.
2. Layered diopside-phlogopite-magnetite-calcite rock with pyrochlore.
3. Monticellite rock, with accessory perovskite.
4. Coarse-grained calcite rock (relatively pure).
5. Very coarse-grained 'pegmatitic' calcite rock.
6. Soda amphibole-calcite rock, with accessory pyrochlore.
7. Melilite-calcite rock
8. Niocalite-calcite rock, commonly with accessory melilite and magnetite
9. Nepheline-calcite rock, commonly with minor melanite and pyroxene
10. Forsterite-calcite rock (rare), with accessory pyrochlore and magnetite
11. Fine-grained apatite-calcite rock

Table 2.2: Okaite Series – five groups of okaite rocks have been identified within the Oka Carbonatite Complex, Quebec (Gold, 1972). In general, the modal mineralogy within okaite includes melilite and pyroxene, commonly with accessory magnetite, apatite and perovskite. Note that the mineral hyne was not present in the okaite analyzed in this study.

1.	Okaite: 60-90% melilite, 40-10% nepheline, hyne, apatite, perovskite, magnetite, phlogopite.
2.	Nepheline okaite: 40% nepheline, 40% melilite, 20% hyne, calcite, magnetite, phlogopite
3.	Hyne-titanian augite okaite: 30% melilite, 10% titanian augite, 40% hyne, 10% phlogopite, apatite, calcite
4.	Jacupirangite: 60%-70% titanian augite, 15-20% nepheline, 2-10% magnetite, 10-15% apatite, phlogopite, perovskite
5.	Apatite okaite: 60-90% melilite, 10-40% nepheline, 10-30% apatite, 5-10% calcite, 5-15% pyroxene, 5-10% phlogopite

Table 2.3: Ijolite Series – Eight groups of ijolite rocks have been identified within the Oka Carbonatite Complex, Quebec (Gold, 1972). In general, the modal mineralogy within ijolite includes nepheline, with accessory calcite, melanite, and apatite.

1. Melteigite: 65% diopside, 35% nepheline 2. Calcite melteigite: 65% diopside, 5-30% nepheline, 5-30% calcite 3. Ijolite: 50% diopside, 50% nepheline 4. Melanite ijolite: 30% melanite, 40% nepheline, 30% pyroxene 5. Melanite-wollastonite ijolite: 25% melanite, 25% wollastonite, 25% nepheline, 25% diopside 6. Calcite ijolite: 50% pyroxene, 20-40% nepheline, 10-30% calcite 7. Urtite: 70-90% nepheline, 10-30% diopside 8. Wollastonite urtite: 55% nepheline, 20% wollastonite, 25% diopside, melanite 9. Titanian andradite

Figure 2.3: Photos from various locations within the Oka carbonatite complex. Photograph A is a view of the Oka complex from the Husereau Hills (area 1). Photograph B shows an ijolitic boudin within a flow-layered carbonatite. Photograph C is a niocalite-carbonatite from trench 4 within the Bond Zone (area 2). Photograph D is a view from the edge of the northern pit (A1), St. Lawrence Mines. Photograph E shows a contact between silicate and carbonate rock on the east side of pit A1, St. Lawrence Mines.

Area A1 - The Husereau Hill

The Husereau Hill (labeled A1 in Figure 2.2) is named after the Husereau family who has owned the 1.2 km long by 400 m wide property for many generations. The crescent-shaped rolling hills are mostly tree-covered (good for maple syrup production) with some regions to the south clear-cut and till-covered used for fruit and vegetable farming (Figure 2.3 photograph A). Several small outcrops of apatite and nepheline okaite, jacupirangite as well as lamprophyric breccia dykes are exposed here. An outcrop of dolomite-carbonatite that was exposed in the 1980's is now covered. Photograph A in Figure 2.3 is a southeast view from Husereau Hill looking towards the Oka Complex.

Area A2 - The Bond Zone

The Bond Zone (located as A2 in Figure 2.2) was the largest niobium ore zone of possible economic value in the Oka Complex (Gold *et al.*, 1986). As a result, the area was aggressively explored in the 1950's and 1960's by means of drill cores and trenches. Vegetation that was once clear-cut has since grown into thick brush. Today the trenches reveal a variety of unusual minerals (such as niocalite, a niobium silicate: $\text{Ca}_{14}\text{Nb}_2(\text{Si}_2\text{O}_7)_4\text{O}_6\text{F}_2$). The Bond Zone contains both carbonatite and ijolitic rocks. The ijolitic rocks occur in discontinuous layers, as rafted blocks, and as boudins that define a zone that is generally parallel to the foliation in the surrounding carbonate rock (Photograph B from Figure 2.3). Photograph C from Figure 2.3 shows a niocalite carbonatite exposed in trench 4 of the Bond Zone with well-developed flow-layering in the niocalite carbonatite rocks (Gold *et al.*, 1986).

Area A3 - St. Lawrence Columbium Mine

In the mid-1950's, zones of pyrochlore-bearing carbonatite were found in a number of locations within the Oka Complex, which had a potential resource of over 200 million tons of low- grade (0.4% Nb₂O₅) niobium ore (Gold *et al.*, 1986). The St. Lawrence Columbium and Metals Corporation Mine and Mill site began production in the early 1960's, which continued until a strike forced them into bankruptcy during 1976 (Gold *et al.*, 1986).

The mine operated for about thirteen years from two open pits: The pit on the northwest side reached a depth of 55 meters and the southeastern pit reached a depth of 110 meters (Gold *et al.*, 1986). Since its closure in 1976, the mine was fenced and abandoned. Although a vast portion of the two pits is submerged under groundwater, some wall faces are exposed (see photograph D from Figure 2.3). Homes and apple farms have been developed on either side of the pits, and access to the mine is still possible. Samples are available from waste rubble piled on the southwest side, as well as the pits themselves. The pits are useful for collecting a variety of different rock types and for viewing the relationships between the different rocks in situ. Photograph E from Figure 2.3 shows a contact between an ijolitic silicate rock (left) and a flow-layered carbonatite (right). Main rock types include various carbonate rocks (niobium-rich, niobium-poor, massive, pegmatitic, layered as well as others), ijolite and glimmerite.

The Nature Centre – Area A4

The Nature Centre (labeled as A4 in Figure 2.2) is part of the Southern Ring Structure (Gold *et al.*, 1986). This smaller, circular ring is about 1830 m by 2440 m in size and consists of carbonatite and ijolite units that dip outward with increasingly steeper dips towards the margin (Gold *et al.*, 1986). The area includes the Oka Provincial Park as well as surrounding homes and farmland. Many outcrops are hidden beneath the homes and other developed urban areas; however, numerous outcrops are accessible within the provincial park. Members of the ijolite series are the dominant silicate rocks exposed. These rocks differ from the northern ring in that they are coarser grained, more abundant in melanite garnet, and can contain wollastonite (Gold *et al.*, 1986). Small outcrops of fenite and nephelinite are exposed near the margin of the Oka Complex.

CHAPTER 3

CARBONATITE

It was not until after 1980 that the International Union of Geological Studies (IUGS) published an official classification of carbonatite (Appendix A). Wooley and Kempe (1989) presented a critique of the IUGS classification with a proposal for improvement (Appendix A).

Carbonatite is defined as “igneous rocks, intrusive as well as extrusive, which contain more than 50% by volume of carbonate minerals” (Woolley and Kempe., 1989). Carbonatite also hosts many interesting accessory minerals such as phlogopite, pyroxene, pyrochlore, magnetite and apatite. To date, approximately 450 carbonatites have been identified around the world that range in age from Archean to recent. Carbonatite is found on almost every continent, and can occur as plutonic (such as Oka, Quebec) to volcanic rocks (such as Oldoinyo Lengai in East Africa). Figure 3.1 shows carbonatite localities and ages within North America and Greenland.

A unique feature of carbonatite is that it contains the highest LREE to HREE ratios, with chondrite-normalized La/Yb ratios up to 740 (Loubet, 1972) and 558 (Hornig-Kjarsgaard, 1997). This chemical “fingerprint” is useful in distinguishing carbonatite from other carbonate rocks. Although modal mineralogy can also be used to identify carbonatite, identification is usually based on chemical composition (Gold *et al.*, 1986).

Carbonatite deposits may include calcite-rich, dolomite rich, iron-rich carbonatite and silico-carbonatite varieties. Carbonatite usually occurs in conjunction with alkali silicate rocks (Bell *et al.*, 1998). Associated igneous rocks are typically nephelinitic or melilititic and include ijolite, melteigite and syenite, as well as their volcanic equivalents. Some carbonatite is associated with Group 1 kimberlites (*e.g.* Premier, South Africa), alnoites (*e.g.* Alnö, Sweden and Oka, Quebec, Canada) or lamprophyres (*e.g.* Kandalaksha, Russia). Host rocks are commonly fenitized (alkali metasomatized) by alkali-rich fluids that migrated from the carbonatite complexes.

The relationship between carbonatitic and associated silicate rocks as well as their genesis and emplacement is still debated in the literature. Carbonatite and carbonatite-alkaline igneous complexes are typically located in relatively stable, intra-plate regions within Precambrian shield or continental platform areas. Some may develop near plate margins or be associated with rifted continental plates and mantle plumes (Gold *et al.*, 1986; Bell *et al.*, 1998). Isotope evidence suggests that carbonatite source melts are generated during asthenosphere-lithosphere interaction. This interaction may be the result of tectonic activity, plume action, or other mantle disruptions (Bell and Blenkinsop, 1987; Bell *et al.*, 1998).

Figure 3.1: Distribution of carbonatite within North America and Greenland (after Woolley, 1989). The research area (Oka Carbonatite Complex) is indicated by the orange star.

CHAPTER 4

PREVIOUS WORK

4.1 GEOCHEMISTRY OF CARBONATITE AND APATITE

Kapustin (1966) published a detailed study of the mineralogical-geochemical characteristics of carbonatite from Siberia, Kola Peninsula and Africa, focusing particularly on the rare earth element (REE) abundances. Although the Oka Carbonatite Complex was not included in his study, Kapustin was one of the first to observe the unique characteristic of carbonatite with its enrichment of rare earth elements. He also noted that a large quantity of trace and REE were concentrated in the carbonate and apatite minerals and, if present, pyrochlore and niobian-perovskite minerals. Kapustin's paper was followed by a number of studies of trace and REE abundances in apatite (and other minerals) within carbonatite suites in Russia, Scandinavia and Africa.

One of the first studies on the general chemistry of Oka Carbonatite Complex was published by Gold in 1963. The information was mostly applied to the production of pyrochlore from St. Lawrence Mine in Oka, Quebec. In the early 1970's, Eby published a number of papers that included the chemistry of apatite from the Oka Carbonatite Complex (Eby, 1973, 1975). The apatite was classified as fluorapatite and noted for its enrichment in REE. In 1975 Eby, using X-ray fluorescence, analyzed whole-rock and mineral samples from Oka for REE and Y abundances. His results showed that all of the chondrite-normalized patterns have a small negative Eu anomaly

for virtually all of the apatite and relatively large enrichment of LREE over HREE.

Eby also observed that all apatite, regardless of rock type, had identical REE abundances.

A more recent paper on the same subject was published by Hornig-Kjarsgaard (1997). The paper focused on REE concentrations in whole-rock samples and of carbonates, apatite, and accessory minerals. The paper compared REE from carbonatite and associated silicate rocks from all over the world, including Oka, Quebec. X-ray fluorescence and microprobe analyses were used for basic chemistry, and ICP-MS (inductively-coupled plasma mass spectrometry, a widely used modern technique for elemental analysis) was used to determine trace element and REE abundances.

Compared to carbonatite suites from other parts of the world, Oka had the highest total REE abundances as well as high LREE to HREE ratios. Hornig-Kjarsgaard (1997) concluded that the concentration and relative enrichment of the REE in most carbonatite and silicocarbonatite with magmatic mineral assemblages is controlled by two mineral phases: carbonates and apatite. Although carbonate minerals have moderate REE abundances (64-3827 ppm), carbonatite has high modal amounts of carbonate minerals (50-99%). Apatite, on the other hand, has only variable modal amounts (0-34%) but high REE abundances (1700-34,000 ppm). The author also noted that because of similar REE distributions in mineral phases and whole-rock, distinct variations in the REE abundances in carbonatite were difficult to explain by fractional crystallization processes. Variations in REE distribution patterns were therefore thought to be signatures of their parental melts.

4.2 ZONATION IN APATITES

Compositional zonation is a common occurrence in rock-forming minerals (Shore and Fowler, 1996). Most of the apatite within the Oka rocks contains compositional zoning not seen under normal transmitted light. The presence of zoned apatite within the Oka rocks raises several questions. First, what is the textural and chemical nature of the zones? Second, what mechanisms cause such abrupt changes in the chemistry between the zones during mineral growth? Is the zonation a primary or a secondary texture? Third, is the zonation due to external or internal forces?

Hogarth (1989) briefly discussed zonation in apatite from carbonatite and fenite in Gatineau, Quebec. Hogarth (1989) used microprobe analyses from each zone (core to rim) to compare the chemical differences. His results showed that apatite has REE and Na enrichment near the rim, and Sr and F enrichment in the core. Hogarth (1989) also noted that these results differed from the carbonatite rocks found at Blackburn Hamlet, Ontario, which is a carbonatite with the same age as Oka (109 Ma). In these rocks, the apatite is enriched in F at the rim, and enriched in REE and Sr in the cores of each grain.

Reeder *et al.* (1989) conducted an experiment in which they produced oscillatory zoning in calcites using a free-drift growth technique. The authors wanted to further understand whether the abrupt fluctuation in chemistry among mineral zones was due to external or internal forces. The experiment involved spiking a solution with Mn during calcite growth and observing the resultant zones using cathodoluminescence (CL). The evidence suggested that the oscillatory zoning in the Mn-doped calcites was

an intrinsic property of the system in a state far from equilibrium and unrelated to external controls. The authors noted that this could be difficult to validate in natural calcites.

Shore and Fowler (1996) studied oscillatory zoning using 75 rock-forming minerals (including apatite). Other than in plagioclase, most zoning is only revealed with sensitive images techniques, including backscattered electron images. Although zonation could be detected using BSE imaging, the authors found the resolution more favourable using Nomarski interference-contrast (NIC) microscopy. The authors ascertained that the variation in the concentration of major elements within an oscillatory-zoned apatite is strongly controlled by crystal chemistry and crystal-liquid equilibria. Trace elements, however, demonstrate much greater variability in concentration, and adsorption of these elements may thus be a mechanism for sector zoning in crystals grown in magmas. The large short-range variations in trace element concentration in some cases of oscillatory zoning in crystals seem to require some form of disequilibrium partitioning. The authors also determined that oscillatory zoning is a primary growth feature.

In spite of these studies, detailed chemical information about each or the zones within individual apatite crystals is not very abundant.

CHAPTER 5

ANALYTICAL RESULTS

Both thin section and grain mount samples were analyzed using the scanning electron microscope (SEM) and wavelength-dispersive electron microprobe at Carleton University. Apatite from twelve samples from four areas throughout the Oka Carbonatite Complex was analyzed for compositional zoning, as well as major and LREE. The concentrations of the HREEs were below the detection limit. The petrological and BSE results are located in Appendix B. The methodology and electron microprobe data results can be found in Appendix C. For the purpose of this study, definitions of major and trace elements are taken from Rollinson (1993). As stated in Rollinson (1993), *major elements* are usually cations that are (presumed to be) accompanied by the appropriate amount of oxygen. The sum of the major element oxides should total to approximately 100%. *Trace elements* are those elements that are present at < 0.1 wt% (Rollinson, 1993). An uncertainty of $\pm 2\%$ is applied to the major element abundances > 5 wt%, an uncertainty of $\pm 3\%$ is applied to the major element abundances between 5 and 0.1 wt%, and an uncertainty of $\pm 5\%$ is applied to the trace element abundances. All uncertainties are quoted at the 2σ level. See appendix C for further detail on sample preparation and analysis.

A total of 135 analyses were made from 55 apatite grains from both silicate and carbonatite rocks. A detailed discussion of the apatite geochemistry among the various

rocks types is given in section 5.1, followed by an account of the compositional zoning in section 5.2.

The general formula for the apatite group is $A_5(BO_4)_3(OH, F, Cl)$. The ideal unit cell formula for the Oka apatite is $Ca_{10}(PO_4)_6(OH)_2$, or hydroxylapatite. A geochemical overview for apatite is as follows. The *A* cations are composed mainly of Ca, which is replaced with minor amounts of Sr, La and Ce (Sr: 0.05 to 0.21 atoms per formula unit (apfu), La: 0.03 to 0.25 apfu, Ce: 0.05 to 0.40 apfu) or trace amounts of Na, Mn, Ba, Pr, Nd, Sm and Y (Gold *et al.*, 1986; Hogarth, 1989). The *B* cation is composed of P, which is substituted with minor amounts of Si (Si: 0.07 to 0.94 apfu) and possibly C (Hogarth, 1989), or trace amounts of S and As (Gold *et al.*, 1986; Hogarth, 1989). The OH anion is replaced by moderate amounts of F (0.6 to 1.15 apfu) and trace amounts of Cl (Hogarth, 1989).

5.1 CHEMICAL CHARACTERIZATION OF APATITE IN DIFFERENT ROCK TYPES

The first section (5.1.1) in this chapter discusses the variation of the major oxides (CaO, P_2O_5 , SiO_2 , La_2O_3 , Ce_2O_3 and SrO). The second section (section 5.1.2) presents a series of graphs with Si plotted against (OH), F, Sr, La and Ce in atoms per formula unit. The similarities between apatite within the carbonatite and silicate rocks are also discussed.

5.1.1 Oxide Variation

The P_2O_5 content for Oka apatite ranges from 30 to 41 wt%. The ranges of the individual rock types are as follows. Apatite from apatite okaite has the lowest P_2O_5 of 30.1 to 35 wt% or 4.8 to 5.3 atoms per formula unit (apfu). Apatite from niocalite carbonatite also has a low P_2O_5 abundance, that ranges from 31 to 35.7 wt% (or 5.0 to 5.3 apfu). Apatite from melanite ijolite and layered carbonatite has P_2O_5 contents that range from 34 to 37 wt% (or 5.4 to 5.7 apfu). Apatite from monticellite carbonatite has a restricted range of 37 to 37.5 wt% (or 5.5 to 5.6 apfu). In contrast, apatite from nepheline okaite and pegmatitic carbonatite has a wide range of P_2O_5 contents from 34 to 40 wt% (or 5.2 to 5.9 apfu). Apatite from the remaining rock types (medium- and coarse-grained carbonatite and calcite ijolite) has the highest range in P_2O_5 content of 38.5 to 41 wt%.

Figure 5.1 is a series of diagrams showing SiO_2 , La_2O_3 , Ce_2O_3 , CaO and SrO (y-axis) plotted against P_2O_5 (x-axis) in wt%. Apatite data from the carbonatite are shown on the left-hand column (i), and data from the silicate rocks are shown on the right-hand column (ii). Carbonatite apatite data are plotted in grey, silicate rock apatite data are plotted in black, and each rock type is represented by a unique symbol. The results are discussed below.

Oxide Variation in samples from Carbonatite:

Figures 5.1A(i), B(i) and C(i) show SiO_2 , La_2O_3 and Ce_2O_3 each plotted against P_2O_5 for the data of apatite from carbonatite rocks. Each plot shows a negative correlation. Apatite from niocalite carbonatite has the highest SiO_2 , La_2O_3 , and Ce_2O_3

contents, and the apatite data from pegmatitic, coarse and medium-grained carbonatite have the lowest contents.

Thus far, two observations are noted for the apatite data from the carbonatite rocks: 1) data from the different rock types plot along a negative linear trend, and 2) the data for each rock type plot in the same arrangement as follows (from high P_2O_5 content to low P_2O_5 content): coarse, medium and pegmatitic carbonatite → monticellite carbonatite + perovskite and layered carbonatite → niocalite carbonatite.

The SrO data in Figure 5.1D(i) do not show the linear trends seen in the previous plots (Figures 5.1 A to C). All carbonatites have a similar SrO content (0.7 to 0.9 wt%), with the exception of the monticellite carbonatite that has a slightly lower range (0.6 to 0.8 wt%).

Figure 5.1E (i) shows CaO plotted against P_2O_5 for the various carbonatites. The apatite data from the niocalite and layered carbonatite have similar CaO values (although different P_2O_5 values). The apatite data from the monticellite, pegmatitic, medium-, and coarse-grained carbonatite also have similar CaO values (although different P_2O_5 values). In general, the data follow a positive trend in a similar arrangement to that observed in Figures 5.1 A to C, column (i).

Oxide Variation in samples from silicate rocks:

The trends defined for apatite from the silicate rocks are very similar to those shown by the carbonatite. P_2O_5 plotted against SiO_2 , La_2O_3 , and Ce_2O_3 shows a negative correlation with a similar slope to the carbonatite rocks (Figures 5.1 A to C, column (ii)).

Figure 5.1: A and B: Plots showing A: SiO₂ vs P₂O₅ and B: La₂O₃ vs P₂O₅ for (i) carbonatites and (ii) silicate rocks. Data from both carbonatite and silicate rocks show a negative correlation along similar slopes. Error bars represent $\pm 2\sigma$ analytical uncertainty.

Figure 5.1 C and D: Plots showing C: Ce₂O₃ vs P₂O₅ and D: SiO₂ vs P₂O₅ for (i) carbonatites and (ii) silicate rocks. Error bars represent $\pm 2\sigma$ analytical uncertainty.

Figure 5.1 E: Plot showing E: CaO vs P2O5 (i) carbonates and (ii) silicate rocks. Data from both carbonate and silicate rocks show a general positive correlation along similar slopes. Error bars represent $\pm 2\sigma$ analytical uncertainty.

Two silicate rock types (apatite okaite and calcite ijolite) contain two phases of apatite growth. The first phase of apatite growth, referred to as the first-generation apatite, are euhedral to subhedral grains that are large compared to the second phase of apatite growth. The second phase of apatite growth is referred to as second-generation apatite and forms anhedral apatite that occurs along grain boundaries as well as within fractures of the larger, first-generation apatite. The second-generation apatite has higher SiO_2 , La_2O_3 and Ce_2O_3 and lower P_2O_5 contents than the first-generation apatite within the same rock. Data from the second-generation apatite also shows negative correlations when P_2O_5 is plotted against SiO_2 , La_2O_3 , and Ce_2O_3 . These negative trends have similar slopes to the first-generation apatite (Figures 5.1 A to C, column (ii)).

The SrO content of apatite from the silicate rocks (Figure 5.1D (ii)) do not show a linear trend seen in some of the previous plots. Data for the various rock types can be divided into two broad groups: those with relatively high Sr-values (SrO averaging 1.0 wt%) and those with relatively low Sr values (SrO averaging 0.6 wt%). Apatite from the nepheline okaite and apatite okaite has higher Sr values than the two ijolites, which range from 0.8 to 1.2 wt%. The apatite from the melanite and calcite ijolites has lower Sr-values that range from 0.5 to 0.7 wt%. There is no difference in the Sr values between first- and second-generation apatite in either the apatite okaite or the calcite ijolite.

The CaO content within apatite from the silicate rocks produces a positive correlation when plotted against P_2O_5 (Figure 5.1E(ii)), similar to that shown by the carbonatite data. The apatite roughly follow the following assemblage (from low to high CaO content): second-generation apatite from apatite okaite → first-generation apatite from apatite okaite → second-generation apatite from calcite ijolite → nepheline okaite and melanite ijolite → first-generation apatite from calcite ijolite. Note that this is the reverse of the sequence given in Figures 5.1 A to C, column (ii).

Oxide Variation between Carbonatite and Silicate rocks:

To summarize the relationship between the carbonatite and silicate rocks:

- 1) Apatite from carbonatite and their associated silicate rocks shares the same linear trends when P_2O_5 is plotted against SiO_2 , La_2O_3 , Ce_2O_3 (negative correlations), and CaO (positive correlation).
- 2) Apatite from niocalite carbonatite share similar P_2O_5 , SiO_2 , La_2O_3 , Ce_2O_3 , and CaO abundances to the first-generation apatite from apatite okaite. There is a wider range in CaO values for the apatite from the apatite okaites than from the niocalite carbonatite.
- 3) Apatite from monticellite carbonatite has similar SiO_2 , La_2O_3 , Ce_2O_3 , and CaO abundances to the two ijolites.
- 4) The first-generation apatite from the calcite ijolite has similar SiO_2 , La_2O_3 , Ce_2O_3 , and CaO values to the apatite from the pegmatitic, medium and coarse-grained carbonatite.

5.1.2 Element variation and substitution

The characteristics of elements within apatite from different rock types are summarized in Table 5.1. The complete results are listed in Table C.4 (Appendix C).

Ions substituting for the Ca^{2+} cation include Sr^{2+} , Na^+ , Mn^{2+} , and LREE. The ions that have replaced P^{5+} include Si^{4+} , C^{4+} and S^{6+} . The ions replacing the $(\text{OH})^-$ anion include F^- and Cl^- . The data for As, Ba, Fe, Na, Mn, Pr, Nd, Sm and Y have very high analytical uncertainties and can therefore not be used in any of the diagrams. Figure 5.2 shows the elements (OH), F, La, Ce and Sr each individually plotted against Si in atoms per formula unit (apfu). The left-hand column shows apatite data from carbonatite, and the right-hand column shows apatite data from silicate rocks.

Element variation for apatite in carbonatite:

The carbonatite apatite shows a systematic variation in Si content depending on the rock type in which it occurs. Apatite from pegmatitic, coarse-grained and medium-grained carbonatites has low Si contents (<0.2 apfu). Apatite from the perovskite, layered, and monticellite carbonatites contains Si of 0.4 to 0.6 apfu, and apatite from the niocalite carbonatite contains the highest Si content of 0.5 to 0.8 apfu.

Figure 5.2 A (i) and B (i) shows F vs Si and OH vs Si. Figure 5.2 C (i) shows (OH)/F plotted against Si. Apatite from almost all carbonatite is classified as hydroxylapatite ($\text{OH}/\text{F} > 1$) other than those from pegmatitic carbonatite and perovskite carbonatite. Apatite from carbonatite with high F (>0.9 apfu) content (*e.g.* pegmatitic carbonatite) contains lower abundances of OH (<1.0 apfu) compared to other

carbonatites. Apatite from carbonatite with a lower F (<0.9 apfu) content contains a higher OH (>1 apfu) content compared with other carbonatites.

Figure 5.2 D(i) and E(i) show La plotted against Si and Ce plotted against Si. Each plot shows a positive correlation. Apatite from the pegmatitic, coarse-grained and medium-grained carbonatites contains the lowest Si and lowest La (<0.06 apfu) and Ce (<0.1 apfu) contents compared to apatite from other carbonatites. Apatite data from the perovskite, layered, and monticellite carbonatites plot further along the slope with higher Si, La (0.04 to 0.12 apfu) and Ce (0.05 to 0.2 apfu) contents. Apatite from the niocalite carbonatite contains the highest Si, La (0.07 to 0.15 apfu) and Ce (0.15 to 0.25 apfu) contents.

Apatite from most carbonatite members have low Sr and variable Si contents, as shown in Figure 5.2 F(i). The Sr content is similar for apatite from all carbonatite samples with values averaging about 0.9 apfu (Figure 5.2 F(i)). The exception is apatite from monticellite carbonatite that contains a Sr content averaging 0.6 apfu. Several apatite grains from the pegmatitic, coarse, and medium-grained carbonatite have a Si content less than or equal to that of Sr. The remaining apatite grains have a Si content greater than that of Sr.

Table 6.1: Summary of characteristic features of minor elements in apatite in atoms per formula unit (apfu) from various rock types from the Oka Carbonatite Complex, Quebec.

Element	Nocallite-carbonatite			Layered-carbonatite			Med-grd-carbonatite			Pegmatitic-carbonatite			Cr-grd carbonatite			Perovskite-carbonatite			Most-carbonatite		
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave
OH	1.35	1.15	1.23	1.11	1.04	1.09	1.12	0.95	1.04	1.02	0.52	0.79	1.22	0.90	1.07	1.17	0.74	0.98	1.33	1.15	1.26
F	0.84	0.64	0.76	0.94	0.88	0.90	1.04	0.87	0.95	1.47	0.99	1.20	1.09	0.78	0.93	1.26	0.82	1.02	0.85	0.67	0.74
OH/F			1.61			1.21			1.09			0.66			1.15			0.96			1.69
Sr	0.11	0.09	0.10	0.09	0.08	0.08	0.09	0.08	0.08	0.10	0.08	0.09	0.09	0.08	0.08	0.09	0.08	0.08	0.08	0.06	0.07
Si	0.82	0.57	0.66	0.52	0.41	0.46	0.17	0.08	0.13	0.34	0.03	0.14	0.13	0.06	0.10	0.51	0.37	0.43	0.38	0.31	0.34
La	0.15	0.09	0.12	0.11	0.09	0.10	0.04	0.03	0.04	0.07	0.02	0.04	0.03	0.02	0.03	0.09	0.07	0.08	0.08	0.04	0.06
Ce	0.29	0.17	0.22	0.20	0.15	0.18	0.07	0.05	0.06	0.11	0.04	0.07	0.07	0.04	0.05	0.15	0.14	0.15	0.15	0.07	0.12
La+Ce			0.33			0.28			0.09			0.11			0.08			0.23			0.18
Element	Nephelinae-apatite			Calcite-apatite 1st			Calcite-apatite 2nd			Melanite-apatite			Apatite-apatite 1st			Apatite-apatite 2nd					
	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave	Max	Min	Ave			
OH	1.08	0.68	1.08	1.17	1.01	1.09	1.09	0.98	1.04	1.19	1.01	1.09	1.45	0.98	1.23	1.49	1.31	1.40			
F	1.32	0.92	1.15	0.98	0.83	0.91	1.02	0.91	0.96	0.99	0.81	0.91	1.02	0.53	0.77	0.69	0.50	0.60			
OH/F			0.94			1.19			1.09			1.20			1.60			2.33			
Sr	0.21	0.08	0.11	0.07	0.05	0.06	0.07	0.06	0.07	0.07	0.06	0.06	0.12	0.09	0.10	0.11	0.09	0.10			
Si	0.60	0.24	0.41	0.15	0.03	0.07	0.53	0.37	0.47	0.46	0.24	0.40	0.85	0.65	0.72	1.06	0.78	0.94			
La	0.09	0.02	0.04	0.05	0.01	0.03	0.13	0.09	0.11	0.07	0.04	0.05	0.23	0.10	0.12	0.29	0.19	0.25			
Ce	0.14	0.02	0.07	0.08	0.04	0.06	0.25	0.19	0.22	0.14	0.07	0.11	0.35	0.17	0.22	0.49	0.29	0.40			
La+Ce			0.11			0.10			0.33			0.16			0.34			0.65

Figure 5.2 A and B: Plots showing A. F versus Si and B. OH versus Si for (i) carbonatite and (ii) silicate rocks. Units are shown as atoms per formula unit (apfu). Error bars represent $\pm 2\sigma$ analytical uncertainty.

Figure 5.2 C and D: Plots showing C: ratio OH/F versus Si and D: La versus Si (apfu) for (i) carbonatite and (ii) silicate rocks. Error bars represent $\pm 2\sigma$ analytical uncertainty.

Figure 5.2 E and F: Plots showing E: Ce versus Si and F: Sr versus Si for (i) carbonatite and (ii) silicate rocks. Error bars represent $\pm 2\sigma$ analytical uncertainty.

Major element variation for apatite in silicate rocks

Similar to apatite from carbonatite, apatite from silicate rocks shows systematic variations in Si content depending on the rock type. Apatite with low Si content (<0.2 apfu) occurs in the first-generation apatite from the calcite ijolite. Apatite from the nepheline okaite, melanite ijolite and second-generation apatite from the calcite ijolite have Si contents of 0.2 to 0.6 apfu. The first-generation apatite from the apatite okaite has a Si content from 0.6 to 0.8 apfu, and the second-generation apatite from the apatite okaite contains the highest Si content that range from 0.8 to 1.1 apfu.

Figure 5.2 A (ii) and B (ii) are plots of F vs Si and OH vs Si. Figure 5.2 C (ii) shows (OH)/F plotted against Si. The nepheline okaite apatite is classified as fluorapatite ($\text{OH}/\text{F} < 1$), whereas apatite from the other silicate rocks is classified as hydroxylapatite ($\text{OH}/\text{F} > 1$).

The plots of La vs Si and Ce vs Si are shown in Figures 5.2D(ii) and E(ii). The apatite data show positive correlations in both plots. The data from the second-generation apatite from the calcite ijolite and apatite okaite have higher La, Ce and Si contents than the first-generation apatite.

The plot Sr vs Si shows that data from the two okaites have higher Sr than both ijolites. (Figure 5.2 F(ii)). Apatite from apatite okaite and nepheline okaite has Sr contents averaging 0.1 apfu, whereas apatite from melanite and calcite ijolite has Sr contents averaging 0.06 apfu. This is similar to the two-fold division found in the plot of SrO vs P_2O_5 (Figure 5.1E(ii)). There are no differences in the Sr abundances between the first- and second-generation apatite. With the exception of a few apatite

grains from the calcite ijolite, apatite from all silicate rocks has a higher Si content than Sr.

Compositional differences in apatite from carbonatite and silicate rocks

The following two conclusions can be made from the apatite data from both carbonatite and silicate rocks:

- 1) The Si, La, Ce, F, OH and Sr abundances from niocalite carbonatite apatite are similar to first-generation apatite from apatite okaite.
- 2) Apatite from coarse and medium-grained carbonatite has similar Si, La, Ce, F and OH values but different Sr values to apatite from nepheline okaite.

Whole-rock carbonatite and associated silicate rocks from Oka generally contain high SrO contents. For example, the SrO content can reach 3.29 wt% in whole-rock carbonatite, and 0.73 wt% in whole-rock okaite (Gold *et al.*, 1986). These values are much higher than that in the Oka apatite, which ranges from 0.06 to 0.1 wt%. It should be noted that Sr is preferentially partitioned into calcite rather than apatite (Pouliot, 1970) which accounts for the lower SrO content in the Oka apatite compared to the SrO content in the Oka calcite.

5.2 APATITE ZONATION

Apatite is a common accessory mineral that is a useful petrological tool because of its sensitivity to subtle changes in the geochemistry of a melt with multi-element components. The compositional zonation within the Oka apatite grains may provide additional information for rock genesis. For the Oka apatite, a “zone” is defined as the

volume area within a mineral grain with homogeneous composition indicated by a uniform colour based on brightness as seen in a backscattered image. This compositional zonation is not visible in transmitted light. Electron microprobe analyses are used to chemically characterize each zone within each apatite grain. BSE images of all grains are evaluated on the basis of: 1) number of zones, 2) the characteristics of each zone, and 3) the textural features of the zones. Two to five electron microprobe analyses were collected from several apatite grains from each rock type.

Most of the apatite from the Oka carbonatite is zoned due to chemical variation in the trace elements, including the REE. Clearly shown in the BSE images are defined zones and textural features such as evidence of resorption and the presence or absence of oscillations (zonation that contain multiple compositionally varying growth shells that are generally parallel to crystallographic planes).

This section is divided into two parts. The first discusses the zonation within the apatite grains based on the relative brightness of the BSE images. The second focuses on the differences in minor and trace element concentrations among the individual zones.

5.2.1 Zonation

Figures 5.3 to 5.8 show BSE images of apatite grains from five different rock types. The figures are shown in two columns. One column outlines the zones from the BSE images, and the second labels the individual zones. The zones are mapped based

on relative brightness and textural features such as resorption (truncations or embayments).

The following is a detailed analysis of the zonation within two carbonatite apatite grains (from the niocalite carbonatite and monticellite carbonatite) and apatite grains from three silicate rocks (from the apatite okaite, nepheline okaite and calcite ijolite).

Zonation within apatite from carbonatite

Niocalite carbonatite: The niocalite carbonatite contains stubby grains of apatite, most $<150\ \mu\text{m}$ in diameter. Figure 5.3 shows four examples of basal sections of apatite with complex zoning. Five zones are recognized in these selected grains from the niocalite carbonatite. The zones are designated one to five in order from the centre of the grain to the rim. Although individual zones may be correlated according to brightness and location within each grain, further analyses are required to establish whether the zones can be correlated and are chemically identical. For the purpose of this study, the similarities and differences of the zones are based on the BSE image. Boundaries between the zones are abrupt in the BSE image. Zone 1 (core) commonly shows a euhedral to anhedral outline and in some cases shows evidence of resorption that takes the form of truncations and/or embayments, such as the apatite grain in Figure 5.3C. In each grain, zone 1 shows sector zonation (sections of compositionally differentiated material). Zones 2 and 3 are euhedral. They appear compositionally uniform and show some evidence of resorption textures. Zones 4 and 5 vary in thickness, are anhedral in shape and commonly display resorption textures. In most

apatite, zones 3, 4 and 5 are either truncated on one side, or vary in thickness around the centre core. For example, the zones in Figure 5.3 B shows a decrease in thickness for zone 2, and a truncated zone 3 on the left-hand side of the grain.

Monticellite-carbonatite: The monticellite carbonatite contains both stubby and prismatic apatite grains. Only the stubby grains are included in this analysis. The stubby apatite grains are anhedral, are commonly <150 μm in diameter, and contain calcite inclusions. Figure 5.4 shows BSE images and line drawings of three grains from the monticellite carbonatite. There are an infinite number of zones recognized in Area 1 within the apatite. This inner area of the grains in Figure 5.4 contains random domains of differentiated material, and the outer area (Area 2) appears a brighter grey on the BSE image that continues to the edge of the grain. Area 2 varies in width around the central core and it is truncated on at least one side of the grains. Both the inner and outer areas are rounded, and the boundaries between the zones are abrupt in the BSE images. There are no indications of resorption texture in either zone, and the calcite inclusions appear to be contained within Area 1.

Zonation within Silicates

Apatite okaite: There are two phases of apatite growth within the apatite okaite silicate rock. The primary phase is referred to as “first-generation” apatite. This apatite is large compared to the “second-generation apatite” (>1 mm in length) and forms prismatic euhedral grains that usually cluster together parallel to their c-axes. As with the apatite from the previous rock types, the zones are correlated according to the BSE

images, and not on their geochemical characteristics. Figure 5.5 shows BSE images and line drawings of three example first-generation apatite grains. The zones within these first-generation apatite are designated 1 to 3 for Figure 5.5 A, and zones 1 to 4 for Figure 5.5 B and C. The zones are arranged from the center of the grain to the rim. Zones cannot be correlated among the grains. That is, although the zones of different grains may share the same number (*e.g.* zone 1 = core), it has not been determined whether the zones are chemically identical. Most of the zones display euhedral outlines and the boundaries between the zones are sharp in BSE images. Zone 1 from Figures 5.5 A and 5.5 C display resorption textures. Zones 3 and 4 from Figures 5.5 B and C show oscillatory zoning. Each euhedral oscillatory zone is $<5\ \mu\text{m}$ in width. In the grains seen in Figure 5.5 A and C, compositionally differentiated material is present within zones 2 and 3. These rounded domains are 5 to $20\ \mu\text{m}$ in diameter and are bright in the BSE image. Almost all zones vary in thickness around the three grains. Zones 2, 3 and 4 can be truncated. It is also interesting to note that zone 1 in Figure 5.5 A and B are a brighter grey, whereas zone 1 from Figure 5.5 C is a darker grey in the BSE images.

The second-generation apatite (*i.e.* the second phase of apatite growth) from the apatite okaite is located either around the outer border or within fractures of the first-

Figure 5.3: BSE images and line drawings of apatite crystals within thin sections from the niocalite carbonatite, Oka Carbonatite Complex, Quebec. The scale bar is located within each photograph. Although further research is required to establish whether the zones can be chemically correlated between the grains, the zones have been numbered. Labeled inclusion in B is cal = calcite.

generation apatite. Adjacent grains control the shape of the second-generation apatite. Figure 5.6 shows BSE images of both the first- (left-hand column) and second (enlargement in right-hand column) generation apatite. No correlation can be made among the zones within the second-generation apatite. All grains and zones are anhedral, although there is possibly of parallel growth, as suggested by the intergranular zonation, especially in Figure 5.6 B (right-hand column). There is also no indication of resorption textures. The vein-like grains are small, averaging $<50\ \mu\text{m}$ in diameter. The zones within the grains are commonly $<10\ \mu\text{m}$ and hence it is difficult to analyze the chemical composition of the individual zones.

Nepheline okaite: The apatite within the nepheline okaite consists of small stubby and prismatic grains, usually with lengths up to 1 mm. The stubby grains are present as inclusions within carbonate grains, and the prismatic grains are located alongside non-carbonate minerals. Grains are euhedral to subhedral, some show a small degree of fracturing and some contain calcite inclusions. Figure 5.7 A shows BSE images of two prismatic apatite grains with multiple oscillatory zones. Grain A1 is a basal section, and grain A2 is viewed along the c-axis. Zones are numbered sequentially from core to rim. Zones cannot be correlated from one grain to another. Most of the zones are subhedral, and some contain resorption textures. Some zones

Figure 5.4: BSE images and line drawings of apatite crystals within thin sections from the calcite monticellite carbonatite, Oka Carbonatite Complex, Quebec. The scale bar is located within each photograph. The inner area of each grain is composed of an infinite number of zones. This region is labeled “Area 1”. The outer area of each grain appears a brighter grey on the BSE image. This region is labeled “Area 2”. The pale yellow inclusions are calcite.

vary in width around the central core, and some zones appear truncated at one end. For example, Figure 5.7 B shows six zones, zone 1 (core) to zone 6 (rim). Zones 1 and 2 are subhedral and are embayed towards the outer margin of the crystal. Zones 3 and 4 are euhedral and vary in thickness around the central core. Zones 5 and 6 are subhedral and show resorption textures. Zone 5 varies in thickness around the central zones. There is little fracturing and calcite inclusions are rare within the grains.

Calcite ijolite: Similar to the apatite okaite, there are two phases of apatite growth within the calcite ijolite. As with apatite from the apatite okaite, the earlier phase is named first-generation apatite, and the later phase is named second-generation apatite.

Apatite within the calcite ijolite is stubby (usually ~200 μm in size) and prismatic (up to 1mm in length). The grains are euhedral to anhedral and show a moderate degree of fracturing. Figure 5.8 shows the BSE images of apatite from the calcite ijolite. The first-generation apatite (*i.e.* the earlier phase of apatite growth) appears dark grey from the BSE image and does not show zoning. This single zone is anhedral to euhedral and appears uniform in composition based on the uniform grey colour from the BSE image. The second-generation apatite is located around the grain boundary, within fractures and/or as “amygdules” within the larger first-generation apatite. The second-generation apatite is generally a brighter grey in the BSE image, and contains complex sector and/or oscillatory zonation.

5.2.2 Composition of the apatite zones

Variation in brightness of the BSE images corresponds to differences in mean atomic number. In the case of the Oka apatite, this variation results primarily from variations in LREE. Figures 5.9 and 5.10 show the geochemical variations among the zones of five apatite grains from three carbonatites (two apatite grains from niocalite carbonatite and one apatite grain from monticellite carbonatite), and two silicate rocks (apatite okaite and nepheline okaite). The BSE images of the grains showing the microprobe traverse across the zones are in column 1. Columns 2, 3 and 4 show the chemical variation in the elements from core to rim. The x-axis reflects the zones, while the y-axis shows the abundance of the various elements. Note that the maximum and minimum values along the y-axis differ from rock type to rock type. Column 2 in Figures 5.9 and 5.10 compares the element abundances of Si and La. The Ce content is plotted along with Sr in column 3. Column 4 is a plot of OH and F contents. Not included in the plots are the major elements (P and Ca) as they do not show significant variation in abundance from zone to zone.

Apatite Zone Composition within Carbonatite

Apatite from the niocalite carbonatite: Figure 5.9 A and B show the results from a microprobe traverse across two apatite grains from the niocalite carbonatite. There is one electron microprobe analysis for each of the five zones. In Figure 5.9 A, zone 1 represents the core, and zone 5 represents the rim. The Si, La and Ce contents show

Figure 5.5: BSE images and line drawings of first-generation apatite crystals from the apatite-okaite, Oka Carbonatite Complex, Quebec. The scale bar is located within each photograph. Although further research is required to establish whether the zones can be chemically correlated between the grains, the zones have been numbered 1 to 5 for convenience. The unlabeled dark inclusions seen in the BSE images are calcite.

Figure 5.6: BSE images of the first- and second-generation apatite from the apatite okaite silicate rock, Oka Carbonatite Complex, Quebec. The column on the left shows BSE images with resolution adjusted for the first-generation apatite. The second-generation apatite is located around the grain boundaries or within crystal fractures appear over-exposed. The second column is an enlargement of the yellow box (from the first column) with resolution adjusted for the second-generation apatite. The scale bar is located within each photograph.

Figure 5.7: BSE images and line drawings of three example apatite grains from the nepheline-okaite silicate rocks, Oka Carbonatite Complex, Quebec. The scale bar is located within each photograph. Although further research is required to determine that the zones can be chemically correlated between the grains, the zones have been numbered for visual convenience.

a similar trend from zones 1 to 5. The Si, La and Ce contents are higher in zones 1, 3 and 5, and lower in zones 2 and 4 (Figure 5.9 A2, A3). There are no changes in the Sr, OH and F abundances. The second apatite grain shown in Figure 5.9 B, zone 1 and 5 represents the rim, and zone 3 represents the core. Once again, the Si, La and Ce content show a similar trend from zones 1 to 5. The Si, La and Ce contents are seemingly higher in zones 1, and 4, and slightly lower in zones 2, 3 and 5 (Figure 5.9 B2, B3). There are no changes in the Sr content. Zone 5 has a slightly higher OH content (and slightly lower F content) compared to other zones within this grain (Figure 5.9 B).

Apatite from the monticellite carbonatite: The apatite from the monticellite carbonatite was analyzed at three locations across the grain (shown in Figure 5.9 C1). The grain is subhedral, about 300 μm in diameter and contains calcite inclusions up to 50 μm in size. There are three zones visible in this grain. Zone 1 (core) is the largest encompassing virtually the entire grain and appears to be a medium grey in the BSE image. Zone 2 is the darkest grey on the BSE image and occurs as a thin layer surrounding the much larger zone 1. Zone 3 is the brightest zone in the BSE image and is located at the margin of the grain. There is a slight variation in Si, La and Ce

Figure 5.8: BSE images of select apatite grains from the calcite ijolite silicate rock, Oka Carbonatite Complex, Quebec. The scale bar is located within each photograph. Photograph A shows an BSE image for the first- and second-generation apatite. Photograph B is an enlargement of the area enclosed by the yellow box, showing the second-generation apatite. Photographs C and D show apatite grains with the first-generation apatite seen as the darker grey (on the BSE grey-scale), and the second-generation apatite as the brighter, commonly overexposed grey.

contents between the zones. Figure 5.9 C2 and C3 show a lower abundance in Si, La and Ce within zones 1 and 3 compared to zone 2. There is no sizable variation in the Sr content. Unlike the apatite grains from the niocalite carbonatite (Figure 5.9 A and B) there is a slight variation in OH and F contents. The OH content increases (and hence the F content decreases) towards the edge of the grain.

Apatite Zone Composition within the Silicate Rocks

Apatite from the apatite okaite: The euhedral apatite from the apatite okaite rock has multiple zones across the grain. The locations of the three electron microprobe analyses are highlighted in Figure 5.10 A1. Zone 1 represents the core and is a darker grey colour in the BSE image. Zone 2a is the brightest zone in the BSE image and represents a region of chemically differentiated material. Zone 3 lies midway between the core and rim. There is no statistically significant variation in Si content, whereas the La and Ce contents are lower in zones 1 and 3, and higher in zone 2 (Figure 5.10 A2 and A3). There is no variation in Sr, OH or F contents.

Apatite from the nepheline okaite: An apatite from the nepheline okaite was probed in each of the three visible zones seen in Figure 5.10 B1. Zones 1 (core) and 3 (rim) are brighter coloured zones, whereas zone 2 is a darker grey on the BSE image (Figure 5.10 B1).

FIGURE 5.9: Series of plots showing the minor element zoning profiles for the selected Oka apatite. BSE images of the apatite in Column 1 show the areas within the grain analyzed by the electron microprobe. Columns 2 to 4 are graphs of the minor element data (in apfu) plotted against the zone number. Row A and B are profiles for an apatite from the niocalite carbonatite. Row C are profiles for an apatite from the monticellite carbonatite. The scale bar for the BSE images are located within each photograph. Error bars represent $\pm 2\sigma$ analytical uncertainty. Note that some error bars are smaller than the symbols used for data points.

FIGURE 5.10: Series of plots showing the minor element zoning profiles for the selected Oka apatite. BSE images of the apatite in Column 1 show the areas within the grain analyzed by the electron microprobe. Columns 2 to 4 are graphs of the minor element data (in apfu) plotted against the zone number. Row A are profiles for an apatite from the apatite okaite (first-generation). Row B are profiles for an apatite from the okaite. The scale bar for the are located within each photograph. Error bars represent $\pm 2\sigma$ analytical uncertainty. Note that some error bars are smaller than the symbols used for data points.

There are large variations of Si, La and Ce abundances among the three zones. Figure 5.10 B2 and B3 shows that zone 3 (the brightest zone on the BSE image) has the highest Si, La and Ce abundances, and that zone 2 has the lowest abundances in these elements. Unlike the apatites from the previous rock types, there is variation in Sr content among the zones. Zone 1 has the highest Sr content with ~0.2 apfu, whereas zones 2 and 3 have about ~0.1 apfu. There is no significant variation in the OH and F contents.

The microprobe work has shown that chemical variations do exist from zone to zone within apatite from both carbonatite and silicate rocks. Notable differences exist in Si, La and Ce contents. The Sr, F and OH contents remain relatively constant.

CHAPTER 6

DISCUSSION

The petrogenesis of carbonatite and associated silica-undersaturated rocks, as well as the relationships among these rock types, has been the subject of discussion for many years. Bell *et al.* (1998) gave a summary of the most outstanding current problems in carbonatite research. These authors concluded that the relationship between carbonatite and their associated silicate rocks is still not completely understood. They further stated that one of the most fundamental questions in carbonatite petrogenesis is whether both rock types were derived from the same parental melt or whether they both formed independently of one another.

In this section, the geochemical analysis of the apatite mineral from the Oka rocks is used to assess some of the following basic questions:

- 1) Are the Oka carbonatite and silicate rocks co-magmatic or are they derived from different sources?
- 2) What is the sequence of magmatic events at Oka?
- 3) What are the possible origins of the apatite zonation?

6.1 GEOCHEMISTRY OF APATITE FROM OKA

The crystallization of apatite depends on three main factors: temperature, SiO_2 content and P_2O_5 content (Watson and Green, 1981; Ronsbo, 1989). Apatite is a useful indicator of petrogenetic processes because it is sensitive to subtle changes in the

concentration of the trace elements (including the REE) during magma evolution (Eby, 1975; Cullers and Medaris, 1977; Ronsbo, 1989; Hughes *et al.*, 1991; Cherniak, 2000).

Previous studies of carbonatite and associated rocks from Oka (Gold, 1963, 1966; Gold *et al.*, 1986; Eby, 1973, 1975) show the following: 1) the various carbonatites were produced in many stages over a long period of time 2) there are three rock series (carbonatite, okaite and ijolite), each made up of several rock members, that were emplaced in the form of cone sheets and ring dykes, 3) calcite and apatite are the main carriers of REE.

Kapustin (1966) was one of the first to demonstrate that the abundances of La, Ce and possibly Nd increase from early to late stage of apatite formation in carbonatite. Kapustin (1966) along with other authors (Balashov and Sharas'kin, 1966; Balashov and Pozharitskaya, 1968; Balashov, 1972; Gerasimovskiy *et al.*, 1972; Eby, 1973, 1975; Cullers and Medaris, 1977; Hughes *et al.*, 1991) have found that changes in the REE contents during the evolution of the magma chamber are reflected in the REE content of the apatite minerals (Balashov and Sharas'kin, 1966; Balashov and Pozharitskaya, 1968; Balashov, 1972; Gerasimovskiy *et al.*, 1972; Eby, 1973, 1975; Cullers and Medaris, 1977; Hughes *et al.*, 1991).

Proposed petrogenetic models for carbonatite and associated silicate rocks include: 1) carbonatite magmas are primary, produced by direct partial melting of the mantle, 2) carbonatite melts are produced by immiscible exsolution from a parental carbonated silicate magma, and 3) carbonatite are the differentiation products (crystal fractionation) of a carbonated alkaline ultrabasic magma. For the Oka Carbonatite

Complex, most authors favour a model involving extensive fractionation of a carbonated silicate melt, which produced many of the silicate rocks as well as the carbonatites. Carbonatitic melts in this model formed as a late-stage product. This model is reviewed later in this chapter but first the results from this thesis are discussed below.

As stated in the previous chapter, the general formula for the apatite group is $A_5(BO_4)_3(OH, F, Cl)$. The unit cell of hydroxylapatite contains $Ca_{10}P_6O_{24}(OH)_2$. Its structure is illustrated in Figure 6.1a. The A ion, commonly composed of Ca^{2+} , can be replaced by Sr^{2+} , Na^+ , Mn^{2+} , Fe^{2+} , Ba^{2+} , Y^{3+} and the LREEs. The B ion is mostly composed of P^{5+} , and can be substituted by Si^{2+} , As^{2+} , S^{6+} and possibly C^{6+} . The apatite from Oka found in this study is mainly hydroxylapatite, but commonly contains appreciable F that has replaced the $(OH)^-$ ion. The Cl content is negligible.

Calcium occupies two distinct positions in the structure: Ca(1) makes up four of the ten positions and is co-ordinated with nine oxygen (Figure 6.1b), and Ca(2) with a multiplicity of six (of the ten positions) is co-ordinated with six oxygen and one fluorine atoms (Figure 6.1c) (Watson and Green, 1981; Watson *et al.*, 1985; Hogarth, 1989; Cherniak and Ryerson, 1993; Cherniak, 2000).

The six PO_4 units of the apatite molecule are organized in sets of three in a “pinwheel” fashion around Ca(1). The P are attached via O(2) and O(3) in each case (Figure 6.1b).

The incorporation of REE into the apatite crystal structure requires a balance during the REE^{3+} substitution for Ca^{2+} in the apatite structure. The types of

substitutions include (Ronsbo, 1989; Hughes *et al.*, 1991; Hogarth, 1989; Cherniak, 2000; Harlov *et al.*, 2003):

The second and third substitutions depend on the alkalinity of the system.

Because the Oka apatite has low Na content, the second and third substitutions are probably negligible compared to the first substitution. It should also be noted that the low S content within the Oka apatite also suggests that the third substituting mechanism involving S^{6+} is minimal for the Oka apatite.

The sum $\text{La}_2\text{O}_3 + \text{Ce}_2\text{O}_3$ varies from about 1.3 to 5.6 wt%, reaching as high as 9.6 wt% for the second-generation apatite from the apatite okaites. The Ca sites within the apatite can effectively discriminate among members of the LREE group according to its atomic arrangement (Hughes *et al.*, 1991; Cherniak, 2000). For example, La and Ce prefer the Ca(2) site, whereas the elements Pr and Sm prefer the Ca(1) site, with Nd substituting equally in both sites (Hughes *et al.*, 1991; Cherniak, 2000). The reason for this discrimination may be due to the slightly larger Ca(1) site (nine-fold coordination with atomic radius of 1.18 Å) than the Ca(2) site (seven-fold coordination with an atomic radius of 1.06 Å), which corresponds well with the ionic radii of the REE (Ca(2): $\text{La}^{3+}=1.10$ to $\text{Nd}^{3+}=1.05$ Å; Ca(1): $\text{Nd}^{3+}=1.163$ to $\text{Sm}^{3+}=1.132$ Å) (Cherniak, 2000). It is therefore thought that the LREE may not behave as a chemically coherent group during substitutions in the apatite structure. It is not clear if there is a difference in the

(a)

(b)

Figure 6.1: (a) Diagram showing the crystal structure of apatite. The green represents the oxygen atoms, blue for calcium atoms, yellow for hydrogen atoms, and red for phosphorous atoms. The numbers on the green atoms represent particular oxygen sites seen in (b) and (c). Calcium occupies two distinct positions in the structure: (b) Ca(1) fills four of the ten positions and is co-ordinated with nine oxygen, and (c) Ca(2) with a multiplicity of six, co-ordinated with six O and one (OH) ion (Hogarth, 1989; Cherniak, 2000). Figure edited from website lyoinfo.in2p3.fr/_cfi/apatites.htm.

(c)

substitution rate of the two Ca sites. Although the REE within the Oka apatite may not behave as a chemically coherent group as has been speculated in the literature, Figures 5.1 and 5.2 show La and Ce are abundant and share a similar trend with Si. Analysis of the remaining REE and comparison of the different LREE to HREE ratios for apatite from different rock types as well as among the zones within one apatite grain would provide additional insights into the substitution of the REE. This would also provide information on the REE fractionation rates and whether the Ca sites can contribute to controlling these rates.

Several other observations can be made with respect to Figures 5.1 and 5.2:

- 1) The abundances of SiO_2 , La_2O_3 and Ce_2O_3 when individually plotted against P_2O_5 , for apatite from both the carbonatite and silicates plot along the same linear slope.
- 2) The data from the carbonatite and silicate rocks types plot in the same order on the graphs as shown in Figures 5.1A, B, C and in the reverse order in Figure 5.1 E. Apatite from calcite ijolite, as well as coarse-grained and medium-grained carbonatite, contains the highest CaO and P_2O_5 abundances, and the lowest SiO_2 , La_2O_3 and Ce_2O_3 abundances. At the other end of the array, apatite (excluding the second generation apatite) from niocalite carbonatite and apatite okaite rocks contains the lowest CaO and P_2O_5 abundances, and the highest SiO_2 , La_2O_3 and Ce_2O_3 abundances of any of the apatites studied.
- 3) The second-generation apatite from the apatite okaite and calcite ijolite silicate rocks has higher SiO_2 , La_2O_3 and Ce_2O_3 contents, and lower CaO and P_2O_5 contents than the first-generation apatite.

- 4) The apatite data from both the silicate and carbonatite rocks plot along lines of similar slope and similar abundances for each graph, with the exception of Sr.
- 5) The Sr data do not lie along a linear trend when plotted against P_2O_5 and SiO_2 (Figures 5.1D, 5.2F).

La+Ce+Si vs Ca+P diagrams

The La+Ce+Si vs Ca+P diagrams (Figure 6.2), which include the data from apatite for both the carbonatite and silicate rocks, best illustrate the REE and Si enrichment in the Oka apatite. The important features that emerge from these diagrams are that the data from both groups of rocks plot along the same linear arrays and that the data overlap. This is clearly shown in Figure 6.3, which is a La+Ce+Si vs P+Ca plot for the apatite from both the carbonatite and silicate rocks. From these diagrams, the following observations can be made:

- 1) The apatite data from both the carbonatite and silicate rocks indicate a negative correlation, and the data lie along one straight line.
- 2) Apatite with the lowest La+Ce+Si and highest P+Ca contents is from the calcite ijolite and pegmatitic, medium- and coarse-grained carbonatite. Apatite with the highest La+Ce+Si and lowest P+Ca contents is from the apatite okaite and niocalite carbonatite.
- 3) Apatite from the melanite ijolite overlap with the apatite from the perovskite carbonatite and monticellite carbonatite.
- 4) The okaites have apatite with <15.1 apfu P+Ca and >0.8 apfu La+Ce+Si. The ijolites have apatite (first-generation) with >15.1 apfu P+Ca and <0.8 apfu La+Ce+Si.

Evaluation of other elements

Strontium is one of the most common replacements in the crystal structure of apatite, readily substituting in the Ca(2) site (Hughes, 1991, Cherniak and Ryerson, 1993). Strontium is also a useful petrogenetic tool because its partitioning is insensitive to changes in melt composition, temperature and H₂O content (Watson and Green, 1981).

Although Sr is competing with La, Pr, Ce and Nd for Ca(2), Sr does not show a linear relationship with either P or Si (Figures 5.1E and 5.2F). This is because the Sr ion is incorporated into the apatite structure as a direct substitution. Both Hughes *et al.*, (1991) and Rakovan and Hughes (2000) analyzed the competition between Sr + La to Nd for the Ca(2) site. They both observed the preference of Sr for the Ca(2) site, which affects the position of the LREE, although it is still not clear why the Sr ion is always preferred relative to the LREE. Figure 6.4 is a plot of Sr vs La+Ce. From this figure along with Figures 5.1E (SrO vs. P₂O₅) and 5.2F (Sr vs. Si), we can observe that:

- 1) Sr shows no correlation with La and Ce (Figure 6.4),
- 2) Sr shows no correlation with Si or P₂O₅ (Figure 5.1 and 5.2),
- 3) Apatite from both ijolites has a slightly lower Sr content (approximately 0.06 ± 0.01 apfu) than the apatite from both okaites (approximately 0.10 ± 0.02 apfu).
- 4) The second-generation apatite from the apatite okaite and calcite ijolite has the same Sr content as the first-generation apatite from the same rocks.
- 5) Apatite from all carbonatites contains similar Sr contents of approximately 0.08 apfu.

A CARBONATITES

B SILICATE ROCKS

Figure 6.2: Plots of cation values as atoms per formula unit (apfu) reflecting the coupled substitution (1) $\text{La}+\text{Ce}+\text{Si}$ vs $\text{P}+\text{Ca}$ for the carbonatite (A) and silicate rocks (B). Both the carbonatite and silicate rocks plot along the same slope. The data points for the apatite okaite (black squares) overlay the data points for the nepheline okaite (black triangles). Error bars represent $\pm 2\sigma$ analytical uncertainty.

Figure 6.3: Plot of La+Ce+Si vs P+Ca reflecting the coupled substitution reaction (1) for apatite cation values from both the carbonatite and silicate rocks. Units are shown as atoms per formula unit (apfu). The data show a negative correlation and lie along the same line. See text for further detail. The data points for the apatite okaite (black squares) overlay the data points for the nepheline okaite (black triangles). Error bars represent $\pm 2\sigma$ analytical uncertainty.

There is a wide variation in the P content in apatite within a single rock type. For example, the P_2O_5 content in the first-generation apatite within the apatite okaite ranges from 31 to 35 wt% (P atoms ranges from 4.8 to 5.36). This wide range in P_2O_5 content is also present in apatite from nepheline okaite, pegmatitic carbonatite and niocalite carbonatite (see Figure 5.1). Such scatter in P_2O_5 is well outside the estimated analytical uncertainties and needs to be explained. Binder and Troll (1989) noted a relationship between P, C and F following an extensive investigation of eighteen apatites from carbonatite, pegmatite, marble and volcanic rocks. The authors concluded that the substitution $P^{5+} + O^{2-} \leftrightarrow C^{4+} + F^-$ is the mechanism responsible for the variation of P within apatite from one rock type. Although this substitution scheme may have taken place at Oka, the relatively linear arrays in the plots involving F suggest that this scheme is unlikely.

The low Cl contents in apatite from the carbonatite and silicate rocks are consistent with those found in other carbonatite complexes (Hogarth and van Breemen 1996; Seifert *et al.*, 2000). Chlorine supposedly goes preferentially into an aqueous fluid phase that may coexist with a carbonatitic melt (Seifert *et al.*, 2000). This Cl- and alkali-rich aqueous fluid is expelled prior to the carbonatite emplacement and reacts with the wall rock causing fenitization (Hogarth and van Breemen, 1996; Seifert *et al.*, 2000).

Figure 6.4: Sr versus La+Ce plot for apatite for (i) carbonatites and (ii) silicate rocks. See text for discussion. Error bar represent $\pm 2\sigma$ analytical uncertainty.

Fractional crystallization model

The initial REE content of the parental alkali-rich melt used for the fractional crystallization model corresponds to a melt produced by 3-5% partial melting of a peridotite containing olivine, orthopyroxene, and garnet (Cullers and Medaris, 1977). The ijolite and okaite silicate rocks are considered the products of fractional crystallization from such a melt. Carbonatite crystallizes at a later stage from a volatile-rich residual liquid. Authors that have studied the magmatic evolution of the Oka Carbonatite Complex generally favour this model.

Table 6.1 summarizes most of the models proposed for the magmatic evolution at Oka. Eby (1973) used the element scandium (Sc) to map the sequence of events in the Oka region. Because Sc shares similar chemical traits to La and Y, Sc readily substitutes for these two elements. Eby (1973) has shown that Sc follows the REE in calcite and apatite. Eby (1975) also analyzed the REE +Y whole rock and mineral concentration from the Oka Carbonatite Complex, and noted that the greatest concentrations occurred in apatite as well as niocalite, perovskite and pyrochlore. Eby also noted that the total REE+Y abundance in calcite and apatite from different carbonatites do not differ from rock type to rock type and that the increase in Sc concentration follows the crystallization sequence previously envisioned by Gold (1966) (see Table 6.1).

Gold *et al.* (1986) published two possible sequences for the magmatic evolution of the Oka rocks. One is based purely on the REE geochemistry, which Gold *et al.* (1986) noted was a suggestion and not a conclusion. Gold (1966), using gravity data, concluded that a cylindrical magma chamber existed at Oka, which trapped volatile elements and led to their accumulation. The carbonatite is thought to have formed from

the volatile-rich melt. Experimental results obtained by Watkinson and Wyllie (1971) suggested that the Oka rocks may be produced by the differentiation of an alkali peridotite magma yielding mafic cumulates then ijolite, then okaite and finally carbonatite. The other paragenetic sequence of Gold (1963, 1972) and Gold *et al.* (1986) consists of nine stages based on detailed structural relationships and petrology.

With the exception of the nine stages published by Gold (1963, 1972) and Gold *et al.* (1986), the sequences proposed in Table 6.1 have some similarities:

- 1) rocks at Oka are considered members of three groups. For example, in the sequence ijolite → okaite → carbonatite, all of the ijolite rock types are grouped together, as are the okaites and carbonatites.
- 2) the ijolite and okaite evolved at an early stage as the result of fractional crystallization from a parental liquid whereas carbonatite crystallized at a later stage from a remaining volatile-rich melt.

Although no isotope work was completed in this study, a detailed Rb-Sr and Sm-Nd isotopic study carried out by Wen (1985) on whole-rocks and mineral separates from the Oka Carbonatite Complex. Wen (1985) showed that there were no systematic differences in the $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios between the carbonatite and silicate rocks. Other isotopic tracer studies, involving C, O and Pb of Oka (Gold *et al.*, 1986; Deines, 1970, 1989; Grunenfelder *et al.*, 1986), which showed that the Oka complex is relatively uniform in its isotopic composition.

The results from this study may generate some concerns for the model of fractional crystallization: These are:

1. Differences in the LREE abundances are present in apatite from various carbonatite rock types, which differ from Eby's findings (1975).
2. Data from apatite within the niocalite carbonatite and apatite okaite overlap in terms of La+Ce+Si and Ca+P abundances (Figure 6.3), which may indicate that both evolved at a similar stage during Oka's evolution.
3. Apatite with low La+Ce+Si abundances may represent those rocks generated at an early stage of Oka's evolution, while those with high La+Ce+Si abundances may represent rocks generated at a late stage of Oka's evolution. The sequence of rock types from low La+Ce+Si to high La+Ce+Si is as follows (as shown in the last row of Table 6.1): for carbonatites the sequence is: medium- and coarse-grained carbonatite → pegmatitic and monticellite carbonatite → layered carbonatite + niocalite carbonatite. The sequence for the silicate rocks is calcite ijolite → melanite ijolite → apatite okaite and nepheline okaite.
4. The similar and overlapping abundances of Ca+P and La+Ce+Si for particular carbonatite and silicate rock types is puzzling. If the increase in REE in the apatite is attributed to crystal fractionation, then it appears from some of the diagrams that silicate and carbonatitic melts co-existed throughout the complete magmatic history of the Oka complex. Rather than carbonatite crystallizing from a late-stage volatile-rich melt produced by fractional crystallization of a parental carbonated, mafic, silicate melt could there be two melts, one carbonatite and one silicate that evolved concurrently? This needs to be investigated further.

Clearly additional trace, REE and isotopic studies on various mineral phases within the Oka rocks are necessary in order to resolve some of the problems that surrounds the relationship between the silicate rocks and the carbonatites.

6.2 APATITE ZONATION

Zonation within igneous rock-forming minerals is a common occurrence (Shore and Fowler, 1996), and minerals within the Oka rocks are no exception. Several minerals show zonation within the Oka rocks, including phlogopite, pyrochlore, pyroxene and apatite (Hogarth *et al.*, 2000, Shore and Fowler, 1996). Some researchers believe that the strong zonation within the Oka apatite can be used to help analyze the conditions within the magma chamber during apatite crystallization. This section focuses on the following issues: 1) the characteristics of the apatite zones (can the zones be characterized as oscillatory, concentric and/or sector zonation?), 2) the compositional differences between the zones for each rock type, 3) the differences in the texture and composition of the zones between the rock types, 4) possible origins of the apatite zonation, and 5) whether the apatite zonation can contribute to understanding the petrogenesis of the Oka rocks. Chemical zonation within igneous minerals is much more common than originally thought. There are several types of mineral zonation recognized in the literature: oscillatory, cyclic, concentric and sector zonation (Figure 6.5). *Oscillatory zonation* is zonation that contains multiple, compositionally different growth shells that are generally parallel to the crystallographic plane and have thicknesses that range from tens of nanometers to several tens of micrometers (Shore and Fowler, 1996). *Concentric zonation* is a form of oscillatory zonation that outlines former growth surfaces, contains

Table 6.1: The progression of rocks during Oka's evolution as published by various authors over the past several decades.

Source	Year	Method	Stages of petrogenesis
Gold	1963	Field relationships	Calcite rocks → melilite-rich silicate rocks, the okaïtes and the nepheline and augite-rich rocks, the jacupirangites → ijolite-urtite series → hydrothermal solutions → alnoite dykes and plugs, and diatreme breccias
Eby	1973	Scandium whole-rock and mineral concentration	Urtite → ijolite → okaïtes → carbonatite → alnoites
Eby	1975	REE + Y whole-rock and mineral concentration	Ultrafenites (juvite and urtite) → ijolite → okaïte → carbonatite
Watkinson and Wyllie	1971	Cumulates due to the differentiation of an alkali peridotite magma	Ijolite → okaïte → carbonatite
Gold <i>et al.</i>	1966, 1986	Petrology and structural field relationships among the various carbonatite and silicate rock types.	<ol style="list-style-type: none"> 1. Fenitization of gneissic rocks by precursor fluids, followed by emplacement as dykes and ring dykes of an early carbonatite phase injected onto ultra-fenites and ijolitized rocks. Remobilized ijolitic rocks may appear either as boudinaged inclusions (early) or as dykes within the carbonatite. 2. Emplacement of early monticellite carbonatite 3. Emplacement of the okaïte-jacupirangite rocks as a crescentic-shaped mass and as a series of concentric arcuate dykes. 4. Intrusion of the main pyrochlore carbonatite followed by emplacement of a late monticellite carbonatite 5. Minor ijolite and microijolite transgressive dykes, many of which are broken into boudin trains 6. Hydrothermal activity along cone-sheet type fractures, causing biotitization and thorium metasomatism 7. Intrusion of late carbonatite and dolomite-carbonatite dykes, some of which carry rare-earth carbonatite, pyrite and galena 8. Late diabase and lamprophyre dykes 9. Emplacement of alnoite, alnoite breccia pipes and dykes. Stages 6 and 9 may be parts of a single event.
Gold <i>et al.</i>	1986	REE geochemistry	<i>Note: this sequence was proposed as a suggestion and not as a conclusion:</i> the sequence melteigite-ijolite-urtite → okaïtes → carbonatite → alnoite
Timmermans	2003	LREE (La + Ce) and Si geochemistry in apatite	For the carbonatites: medium+coarse-grained carbonatite → pegmatitic + monticellite carbonatite → layered carbonatite → perovskite carbonatite → niocalite carbonatite. For the silicate rocks: calcite ijolite → melanite ijolite → apatite okaïte+ nepheline okaïte.

Figure 6.5: Graphical representation of possible zonation within the Oka apatite. (a) and (b) are examples of oscillatory zonation, (a) shows concentric zonation and (b) shows cyclic zonation. (c) is an example of sector zonation. The various brightness represents different compositions. See text for definitions.

non-repetitive compositional changes and provides a record of crystal morphology and of chronological changes in the system (Reeder *et al.*, 1989). Concentric zoning patterns are most commonly interpreted as reflecting temporal changes in properties of the bulk fluid from which crystallization occurs (Reeder *et al.*, 1989). These temporal changes may involve bulk composition, redox state, temperature and/or pressure. *Cyclic zonation* is also a form of oscillatory zonation that outlines former growth surfaces and contains repetitive compositional changes. *Sector zonation* is zonation represented by a compositional difference between time-equivalent, but symmetry – nonequivalent, growth sectors (Reeder *et al.*, 1989). That is to say, sector zonation does not record chronological differences in the state of a system.

Zonation within apatite from Oka

All of the Oka apatite shows some degree of oscillatory and/or sector zonation. This section uses the zoning within the Oka apatite to: 1) define the type of zonation (*i.e.* concentric, cyclic and/or sector) and see whether it is consistent within a given rock sample, and 2) compare the type of zonation among different samples.

Most Oka apatite usually has two to three oscillatory zones. Two samples, the niocalite carbonatite and apatite okaite, contain apatite with five or more oscillatory zones and various degrees of sector zones. The calcite ijolite and monticellite carbonatite contain apatite with primarily sector zonation (Figures 5.6 and 5.10). A detailed description of the apatite zonation within each rock type can be found in Chapter 5 or Appendix B. Note that apatite from most rock types contains zones with resorption textures.

Only the apatite okaite and calcite ijolite possess two separate generations of apatite. The second-generation apatite is anhedral, taking on irregular snake-like shapes (Figure 5.8 and 5.10). It is located around grain boundaries or within fractures of the much larger first-generation apatite. The second-generation apatite typically contains two to three oscillatory zones, as seen within the basal section from Figure 5.8A, right-hand column.

It is interesting to compare the apatite zoning from Oka with other studies. Hogarth's (1989) analyses of carbonatite from the Gatineau area, Quebec, indicate that apatite possesses concentric zones, which shows from core to rim enrichment in REE+Na and depletion in Sr+F. Two carbonatite samples from the Siilinjärvi Carbonatite Complex, eastern Finland, were also included in the BSE images analysis. The apatite

within the Siilinjärvi carbonatite forms subhedral stubby grains reaching several millimeters in length. The Siilinjärvi apatite grains do not contain or show only slight zonation. Figure 6.6 shows BSE images of four examples of stubby apatite grains. A few grains appear to have a faint zone at the rim, but this may be due thinning of the apatite at the edges during sample preparation. The nearly uniform brightness implies that these apatite grains are compositionally homogeneous, although further chemical analysis is needed. No further analyses were attempted in this study.

Comparing apatite from Oka with apatite from carbonatite from Gatineau and Siilinjärvi reveals that zoning within the Oka apatite may differ in both its character and chemistry. This fact becomes relevant when discussing the possible origins of the apatite zoning later in this chapter.

Compositional variation of the zones

Apatite zonation is evident in BSE images because of differences in the mean atomic number of the mineral growth-zones (Tepper and Kuehner, 1999). For Oka apatite, changes in brightness on the BSE image result from variation in LREE abundances. The results of the microprobe analyses of the various zones within individual grains, however, show that these changes mainly correspond to variations in both the LREE and Si abundances. The concentrations between each zone vary up to 0.2 apfu for Si, and 0.1 apfu for La+Ce. The behaviour of Si differs only in the apatite okaite sample #136, where the Si-content does not vary between zones (see Figure 5.10 A). It should be noted, however, that other apatite grains within the other apatite okaite samples (#138) vary in Si-content (up to 0.1 apfu, see Appendix C).

There are also compositional differences between first- and second-generation apatite. When compared to first-generation apatite, the second-generation apatite is enriched in La+Ce+Si, and depleted in P+Ca. However, the Sr content does not change between zones, nor does the content vary between the first- and second-generation apatite. It is noted, however, that Sr content does vary within the apatite from the nepheline okaite (Figure 5.10 B4). This particular grain seems unique as measurements of other nepheline okaite apatite grains within the same rock sample do not show Sr variation between zones (see Appendix C).

6.2.1 Possible origins for apatite zonation

The zonation within apatite from Oka is recognized as a primary growth-texture (Hogarth, 1989). A model that explains the origins and development of the apatite zones within the Oka rocks must address the following: 1) the presence of zones in all apatite throughout the Oka Complex, 2) the various types of zones found in different rock types, 3) the abrupt versus gradual shifts in chemical composition between each zone, 4) the presence of zones within both first- and second-generation apatites, 5) the occasional cyclic variation in La+Ce+Si abundances (Figure 5.9 and 5.10), 6) the consistent abundance in Sr, and 7) evidence of resorption in some apatite grains.

Figure 6.6: BSE images of apatites from the Siilinjärvi Carbonatite Complex, Eastern Finland. These images show no zonation (appear compositionally homogeneous), unlike the apatite from the Oka Carbonatite Complex. The scale bars are located within each photograph.

Research has shown that compositional zoning in igneous minerals can result from several processes, including magma mixing, changes in crystal/melt element partitioning and kinetic effects (Tepper and Kuehner, 1999). This section evaluates these three processes plus other possible explanations for trace and RE element zoning in apatite from the samples from the Oka Complex.

Models attempting to explain complex mineral zonation patterns are commonly based on either of two different assumptions: the zonation mainly reflects changes in external geological processes during crystal growth (extrinsic mechanisms), or the zonation is the result of internal crystal growth processes (intrinsic mechanisms; Shore and Fowler, 1996). These two concepts are discussed below.

Extrinsic mechanisms involve physical or chemical changes within the bulk system that are partially or wholly independent of local crystallization, such as crystal settling, large-scale convection, fluid mixing, and reservoir replenishment. (Shore and Fowler, 1996). The apatite/melt distribution coefficients for many minor elements are typically >1 (Watson and Green, 1981; Tepper and Kuehner, 1999; Cherniak, 2000). Apatite is therefore more sensitive than most rock-forming minerals to minor changes in the trace and REE concentrations that can occur during igneous processes. Evidence also shows that Si is probably involved in the LREE abundance variation because both vary, for the most part, in a complementary manner (Figure 5.9 and 5.10 column 2). The substitution $\text{Ca}^{2+} + \text{P}^{5+} \leftrightarrow \text{REE}^{3+} + \text{Si}^{4+}$ may not be the primary mechanism causing the REE variation within a grain as the abundance of Ca and P shows little variation across the grain.

Zoning may be caused by changes in the rate in which the REE are incorporated into the apatite crystal structure, which can be affected by temperature and Si content. Si is the rate-limiting ion for the substitution $\text{Ca}^{2+} + \text{P}^{5+} \leftrightarrow \text{REE}^{3+} + \text{Si}^{4+}$, because it is more difficult to incorporate the Si ion within the tetrahedral matrix. There is also considerable variation in the rate at which certain REE are incorporated into the Ca(1) or Ca(2) sites (Cherniak, 2000) that may be affected by external forces. Although beyond the scope of this study, it would be interesting to compare the degrees of fractionation of LREE to HREE among the zones within an apatite. There may be another exchange in operation within the Oka apatite that involves $\text{REE}^{3+} + \text{Si}^{4+}$.

Convection within a magma chamber could cause subtle changes in the pressure, temperature and/or chemical composition that may affect the REE+Si exchange within the apatite molecule. Several rock types show evidence to support this theory. For example, certain rocks types, such as the monticellite carbonatite, do show cumulate textures and there are many examples of layered carbonatite rocks within the Oka Complex (see appendix B). In addition, the trachytic textures within the apatite okaite are formed by the orientation of prismatic apatite (see Figure B.5, photograph C in Appendix B). It should be noted that in some cases the apatite within the apatite okaite are oriented in the same direction, whereas in other cases the grains are radial. Therefore, it is possible that these textures are the result of other dynamics rather than those due to external forces.

Convection also accounts for the various pressure, temperature and chemical conditions within different areas of a magma chamber. In other words, distinct areas within a convecting magma chamber would be impacted by unique external conditions.

Another external mechanism that may account for apatite zonation and the structural characteristics of the Oka Complex is a pulsing magma source. A pulsing magma source with flow differentiation in the overlying conduit could yield the well-developed layering (flow fabric) in the carbonatitic rocks as well as the concentric lithostructural units with contrasting mineralogy. This model could account for the cyclic zones seen in many Oka apatite as well as the constant Sr abundances. Concerns with this model include the presence of complex sector zones in many Oka apatite.

Most Oka apatite exhibit oscillatory zonation, which may be due to continuous changes in the external conditions during crystal growth. Complex sector zoning in apatite from rock types such as the monticellite carbonatite (Figure 1.1e and f) may simply be due to multiple nuclei within an individual apatite grain. In the example shown in Figure 1.1e, each region of compositionally different material could represent a distinct nucleus. For the apatite shown in Figure 1.1f, external conditions may have favoured numerous stable nuclei for one half of the grain, and the conditions for stable nuclei were less favourable for the other half of the grain. This model warrants further research that is beyond the scope of this thesis.

Other extrinsic models such as crystal settling, reservoir replenishment or fluid mixing would cause zonation within the Oka apatites. These models, however, do not explain the cyclic nature in REE+Si abundances, nor the various types of zonation found among different rock types. Crystal settling, reservoir replenishment or fluid mixing is more likely to cause concentric zonation from core to rim, as well as similar zoning patterns in the various rock types.

All this being said, there is an argument to support a convecting magma chamber as an external mechanism that would cause zoning within the Oka apatite. Before making any conclusions, however, intrinsic models should be assessed.

Intrinsic mechanisms link crystal growth to purely local phenomena, involving coupling between the rate of crystal growth and solute diffusion through the crystal-melt boundary layer (Shore and Fowler, 1996). Most intrinsic models involve a feedback mechanism between crystal growth and solute diffusion or surface effects as a source of non-linear behaviors in the crystal-growth kinetics (Shore and Fowler, 1996). Reeder *et al.* (1989) performed a controlled experiment analyzing zoning of Mn in calcite crystals. The authors produced interesting results. Factors that affected zonation included temperature, growth rate and distribution coefficient (which they defined as $k = (A/B)_{\text{solid}}/(A/B)_{\text{liquid}}$, where A is the substituent ion, and B is the original unit ion). It was found that there was no general correlation of the periodic subzones with the number of days of growth. Furthermore, the authors were generally unable to correlate the number of subzones between crystals. For example, in a given reaction vessel, the total number of distinct subzones was found to vary between nine and twenty-three for the same period of growth. The authors proposed a model based on the growth rate attenuation with Mn^{2+} and the effect of growth rate on the distribution coefficient.

In their model (Reeder *et al.*, 1986), the growth rate decreases due to Mn adsorption on the calcite surface. As the growth rate decreases, the distribution coefficient increases, resulting in a relative depletion of Mn at the interface and consequently decreased adsorption, which then allows the growth rate to increase. The increased growth rate causes the distribution coefficient to decrease. Diffusion then

allows Mn levels to recover near the interface, and the cycle repeats. Thus, if the rate-limiting step is purely surface-reaction controlled, then temporal variations in Mn concentration at the interface are unlikely (Reeder *et al.*, 1986).

Reeder *et al.* (1986) point out that it is difficult to apply a laboratory-controlled model utilizing calcite to apatite minerals in a natural environment. However, the model cannot be presently ruled out. It is possible that during apatite growth, the narrow region surrounding the crystal would become depleted in the growth elements and enriched in the trace and REE with respect to the bulk liquid. The interplay of chemical diffusion, chemical exchange, thermal diffusion and crystal growth rate may result in the zonation within the apatite grains from Oka. Although this model may explain the presence of zonation found in many of the rock-forming minerals in the Oka Complex, as well as the cyclic chemical nature of the zonation pattern, it does not explain the abrupt versus gradual changes in chemistry between each zone. It does not explain the presence of zonation in Oka apatite, and the absence of zonation in Siilinjärvi apatite. It also does not explain the presence of resorption textures within some Oka apatite grains. Zoning should also be affected by the surrounding mineral phases, for which there is not evidence. Research involving measuring the physical parameters required for this or variations of this model is beyond the scope of this thesis. Further investigation in this area is encouraged.

Cressey *et al.*, (1999) analyzed sector zonation in monazite ((Ce, La, Nd, Th)PO₄), another important host mineral for the REE. Monazite from within the Kangankunde carbonatite, Southern Malawi, was analyzed for its chemical variation among sector zones. In this study, sector zonation is defined as pie-shaped, kinked zones

representing time-equivalent growth (unlike the definition used for the Oka apatite). The authors attributed the zonation to variation in the REE, where different growth surfaces would take up various REE ions (Cressey *et al.*, 1999). The differences in atomic structure on different growth surfaces are directly related to the variation in the REE chemistry between the zones. Although this mechanism accounts for the abrupt boundaries between the zones, it does not seem applicable to the Oka apatite for the following reasons. The sector zones within the Oka apatite is much more random than the Kangankunde monazite. In addition, the Oka apatite does not follow the apatite crystal structure as with the monazite from Kangankunde.

There is another possibility for the sector zoning within the Oka apatite. As mentioned earlier in this chapter, it is possible that each zone represents a separate nucleation stage. For example, the apatite shown in Figure 1.1e contains numerous zones throughout the grain. Each zone centre may represent a nucleus. The apatite in Figure 1.1f contains sector zoning in one half and not in the other. Perhaps nucleation was more rapid in one half at the time of growth. This model also merits further scrutiny.

To summarize, the origins of the Oka apatite zoning remains inconclusive. There is sufficient textural evidence within the Oka rocks to support the possibility of a convecting magma chamber or a pulsing magma source. However, the possibility of intrinsic forces contributing the development of the apatite zonation cannot be dismissed. Further trace and REE abundance studies and detailed isotopic research could help develop a model for the origins of the apatite zonation found in the Oka rocks.

CHAPTER 7

CONCLUSIONS and RECOMMENDED FUTURE WORK

The results from this study have revealed some interesting findings

1. The OH/F indicate that the majority of the Oka apatite is hydroxylapatite. Apatite from two of the rock types, nepheline okaite and pegmatitic carbonatite, is classified as fluorapatite.
2. Apatite from the various carbonatite and silicate rock types from Oka vary in their Ca+P and La+Ce+Si abundances.
3. The REE are incorporated into the Oka apatite crystal structure primarily by the coupled substitution: $\text{Ca}^{2+} + \text{P}^{5+} \leftrightarrow \text{REE}^{3+} + \text{Si}^{4+}$.
4. Certain carbonatite and silicate rocks overlap in their Ca+P and La+Ce+Si abundances.
5. Based on the REE abundances, the magmatic evolution of the Oka rocks are as follows: For the carbonatites: medium and coarse-grained carbonatite → pegmatitic and monticellite carbonatite → layered carbonatite and perovskite carbonatite and niocalite carbonatite. For the silicate rocks: calcite ijolite → melanite ijolite → apatite okaite and nepheline okaite.
6. Almost all apatite from the Oka Complex shows zonation. The type of zonation found in apatite from various rock types are characterized as oscillatory and sector zoning.
7. Zoning in Oka apatite is due to variation in REE content.

8. The origins of the Oka apatite zoning remain inconclusive. There is enough textural evidence within the Oka rocks to support the possibility of a convecting magma chamber or a pulsing magma source, although the possibility of intrinsic forces contributing the development of the apatite zonation also cannot be dismissed.

This study has shown that major and trace element (including REE) studies can be used to characterize the similarities and differences in the various rock types from a carbonatite suite. These data can be used to help understand the relationship between carbonatite and associated silicate rocks and melt evolution within a magmatic system. For the rocks from Oka and other carbonatite suites, additional trace and REE analyses as well as detailed isotopic research is recommended to:

1. further explore the second-generation apatites: are they present in other rock types? How and when did it crystallize?
2. develop a plausible model for the origins of the apatite zonation.

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APPENDIX A

CLASSIFICATION OF CARBONATITE

A.1 International Union of Geological Sciences:

1. Carbonatite are igneous rocks, intrusive as well as extrusive, which contain more than 50% by volume of carbonate minerals.
2. The following classes of carbonatite are distinguished:
 - a. Calcite-carbonatite (sövite, coarse-grained; alvikite, medium-to-fine-grained);
 - b. Dolomite-carbonatite (rauhaugite)
 - c. Ferrocarbonatite (essentially composed of iron-rich carbonate minerals);
 - d. Natrocarbonatite (essentially composed of sodium-potassium-calcium carbonates; this rock is known only as the extrusive product of Oldoinyo Lengai volcano in northern Tanzania).
3. Carbonatite containing a mixture of various carbonate minerals, *e.g.* calcite and dolomite, are indicated by prefixes according to the established rules for quantitative composition of rocks at the 10-50-90% boundaries. The qualification dolomite-bearing, etc., may be used when the presence of the minor constituent (less than 10%) needs to be emphasized.
4. Igneous rocks containing less than 10% carbonate minerals may be called calcite-bearing ijolite, dolomite-bearing peridotite, etc.
5. Igneous rocks containing between 10 and 50% carbonate minerals are called calcitic (or carbonatitic) ijolite, etc.

6. The terms melanocratic and leucocratic should not be applied when describing carbonatite.
7. Characteristic contents of other minerals are indicated by prefixes: apatite-pyrochlore-carbonatite, aegirine-calcite-carbonatite, magnetite-dolomite-carbonatite, etc.

A.2 Addition to the Classification of Carbonatite, Woolley (1996).

This classification should be used only if the rock contains more than 50% modal carbonates. Carbonatite may be either plutonic or volcanic in origin.

Mineralogically the following classes of carbonatite may be distinguished.

1. Calcite-carbonatite - where the main carbonate is calcite. If the rock is coarse-grained it maybe called sövite; if medium to fine-grained, alvikite
2. Dolomite-carbonatite-where the main carbonate is dolomite.
3. Ferrocarbonatite - where the main carbonate is iron-rich.
4. Natrocarbonatite - essentially composed of sodium, potassium, and calcium carbonates. At present, this unusual rock type is only found at Oldoinyo Lengai volcano in Tanzania.

Figure. A1. Chemical classification of carbonatite using wt% oxides (Woolley and Kempe, 1989).

Qualifications, such as dolomite-bearing, may be used to emphasize the presence of a minor constituent (<10%). Similarly, igneous rocks containing less than 10% of carbonate may be called calcite-bearing ijolite, dolomite-bearing peridotite, etc. Igneous rocks with between 10% and 50% carbonate minerals may be called calcitic ijolite or carbonatitic ijolite, etc. If the carbonatite is too fine-grained for an accurate mode to be determined or if the carbonates are complex Ca-Mg-Fe solid solutions then the chemical classification shown in Figure A.1 can be used.

APPENDIX B

SAMPLE DESCRIPTIONS

Drs. K. Bell, J. Wen and Ann Timmermans collected about 150 samples from the Oka Carbonatite Complex and surrounding areas from the years 1985 and 2001. Seven carbonatite and four silicate rock samples from four locations within the Oka Complex were selected for this study. Thin sections were prepared for most samples. Apatite grains were also separated from several rock samples and placed into grain mounts. Some samples were obtained from mineral separates used in a 1985 thesis study by Jianpang Wen (Carleton University) who completed a Sr and Nd isotope study of carbonatite and silicate rocks from Oka. Although the mineral separates remained available for this study, the hand samples and thin sections no longer existed. Samples include:

LOCATION	ROCK TYPE	YR COLLECTED	SMPL PREP	
Bond Zone	Niocalite crb	1986 and 2001	HS, TS	Carbonatites
Bond Zone	Perovskite crb	1985 and 2001	GM	
St. Lawrence Mine	Layered crb	1985	GM	
St. Lawrence Mine	Monticellite crb	1997	HS, TS	
St. Lawrence Mine	Medium-grained crb	1985	GM	
St. Lawrence Mine	Coarse-grained crb	1985	GM	
St. Lawrence Mine	Pegmatitic crb	2001	GM	
St. Lawrence Mine	Calcite ijolite	1997	HS, TS	Silicate Rocks
Nature Centre	Melanite ijolite	1986	HS, TS	
Husereau Hill	Apatite okaite	2000	HS, TS, GM	
Husereau Hill	Nepheline okaite	1997	HS, TS	

(crb = carbonatite, HS = hand sample, TS = thin section, GM = grain mount)

The following is a detailed description on the hand sample, petrology and the apatite zoning seen in the BSE images for each sample.

B.1: Sample Descriptions

1986oka.A2.004 and 152: Niocalite carbonatite, Bond Zone

Hand Sample: Sample 004 is a coarse-grained niocalite carbonatite from the Bond Zone. The outcrop is exposed from the fourth trench excavated during the 1950's. The carbonatite is a friable, cream coloured rock when fresh, a dirty tan to light brown when weathered. The grains average 1-2 mm in diameter with approximately 10% mafic minerals (Figure B.1-A). Leucocratic minerals composed of calcite (>50%), niocalite, melilite and apatite. Mafic minerals consist of phlogopite, pyroxene, pyrochlore and magnetite.

Petrology: Mineralogy includes >50% calcite, as well as niocalite, phlogopite, apatite, pyrochlore, perovskite, magnetite, melilite and sodian augite. The calcite grains (50% modal abundance) are subhedral to anhedral and range about 1-3 mm in diameter. A small percentage contains apatite inclusions. The calcite grain boundaries are sharp and exsolution is present along the cleavage planes within grains. The apatite (10% modal abundance) is euhedral. Most apatite forms stubby grains, although prismatic grains are also seen. The apatite is located between grain boundaries and as inclusions (Figure B.1-B). The apatite ranges from 0.1 to 0.2 mm in length and appears to contain no mineral inclusions. Niocalite (10% modal abundance) closely resembles a “fat” apatite in that they are slightly larger in width, and are prismatic with parallel fractures “segmenting”

the grain. The melilite (5% modal abundance) is anhedral and ranges 1-2 mm in diameter. Most of the melilite is altered. Calcite, apatite and augite inclusions are present in almost all the melilite grains. The sodian augite (5% modal abundance) is subhedral, typically contains inclusions, and range from 0.1 to 0.5 mm in diameter. The grains possess altered material around the borders and within the grain. Calcite and apatite are commonly present as inclusions. The phlogopite (5%) is anhedral and ranges from 0.1 to 1 mm in diameter. The phlogopite shows a high degree of alteration and contains numerous inclusions. Monticellite (10% modal mineralogy) is subhedral, up to 1 mm in diameter and typically contains apatite inclusions. Anhedral oxides make up about 10% of the rock and commonly contain calcite and/or apatite inclusions.

Zoning: Apatite from the niocalite carbonatite is fractured and contains calcite inclusions. All apatite is zoned. Zones are best viewed when grains are cut along the c-axis. Most apatite grains contain up to five oscillatory zones. Many grains contain a subhedral central zone that contains additional sector zoning. Other zones are subhedral to euhedral from 5 to 50 μm in thickness (Figure B.1-C and D). Although generally similar, detailed zonal patterns differ from grain to grain. Borders between zones are abrupt and may show resorption texture.

2000oka.A1.146 – Perovskite-bearing carbonatite, Bond Zone

Hand Sample: This sample was obtained from Trench 4 within the Bond Zone. The carbonatite is equigranular coarse-grained with 70% leucocratic minerals and 30% mafic minerals. Grain size is approximately 1-2 mm. Felsic minerals include calcite (>50%), melilite and apatite. Mafic minerals include subhedral to euhedral magnetite (>15%), euhedral perovskite and phlogopite (<5%) (Figure B.2-A).

This sample was crushed, apatite hand picked, and then placed in a grain mount. No thin section was prepared.

Zoning: Apatite is stubby averaging 0.5 to 1.0 mm in length. Zones are difficult to characterize when the apatite grains are viewed along the c-axis (opposed to viewed perpendicular to the c-axis), as is the case for these mounted apatite grains. Therefore, only general observations of the zones are possible.

Each grain contains three to four anhedral to subhedral oscillatory zones. Sector zoning is also seen in several grains (Figure B.2 B, C and D). It is difficult to recognize the presence of resorption textures viewing the zoning along the c-axis. The boundaries between zones are abrupt.

1997oka.A3.092 – Pegmatitic Carbonatite, St. Lawrence Mine

Hand Sample: Phlogopite-bearing pegmatitic calcite carbonatite collected from the St. Lawrence mine pits. This rock contains 90% light-coloured minerals and 10% mafic minerals. The light-coloured minerals are mostly euhedral to anhedral calcite grains that range from 1 mm to several cm in size. Other light-coloured minerals include anhedral melilite and/or nepheline in addition to euhedral apatite. Almost all of the mafic minerals are euhedral phlogopite up to 4 mm in size. Trace amounts of oxides, pyrochlore, pyroxenes and other mafic minerals may be present but require probe identification. Only grain mounts were prepared for this sample.

Zoning: Apatite is >1 mm in size and subhedral to euhedral. Fracturing is minimal and almost all grains contain numerous large calcite inclusions. Grains show minimal zoning, although this may be due to the fact that each grain is observed only along the c-axis. There are typically two oscillatory zones ~100 µm in thickness, and the borders between the zones are abrupt.

2000oka.A3.124: Coarse-grained monticellite carbonatite, St. Lawrence Mine

Hand-Sample: This coarse-grained carbonatite was obtained from the St. Lawrence Mine. The sample is equigranular, containing about 70% leucocratic and 30% mafic minerals (Figure B.3 A). Modal mineralogy includes subhedral calcite (~55%, 0.5 to 1mm in diameter), apatite (~10%), nepheline (<10%), monticellite, pyrochlore, pyroxene and phlogopite. See next section for further detail.

Petrography: Euhedral to anhedral calcite grains (55% modal abundance) are up to several mm in diameter. Monticellite (15-20% modal abundance) is euhedral to subhedral, typically <1mm in diameter and contains apatite and calcite inclusions. Pyroxene (15% modal abundance) is small (<0.5 mm), anhedral and also contains inclusions. Stubby apatite (10% modal abundance) is typically < 1mm in length (Figure B.3 B). Pyrochlore (<2% modal abundance) is euhedral, and typically <2 mm in diameter. Some apatite crystals cut across the pyrochlore. Nepheline (5% modal abundance) is anhedral, <2 mm in diameter and mostly located between the calcite grains. Patches of altered material are commonly present in thin section.

Zoning: Apatite within the monticellite carbonatite is both stubby and prismatic. The stubby grains are smaller (<0.05mm) than the prismatic grains, usually without fractures and do not contain inclusions. The prismatic grains, however, have a higher degree of fracturing and contain numerous calcite inclusions. The stubby apatite contains complex sector zoning (Figure B.3 C and D). The inner area is composed of many small, rounded zones, whereas the outer area is brighter in the BSE image and continues to the edge of the grain. In some grains this outer area is truncated on one side.

1997oka.A4.089: Melanite ijolite, Nature Center

Hand Sample: Sample 089 is a coarse-grained ijolite from the Nature Centre. The rock contains 60-70% leucocratic minerals and 30-40% mafic minerals. The minerals range from 2-5 mm in diameter. Minerals include nepheline, calcite, euhedral melanite, pyroxene and magnetite. Nepheline is pinkish in colour, probably due to weathering (Figure B.4-A).

Petrography: Calcite (20% modal abundance) is anhedral to subhedral and can reach up to several millimeters in diameter. Calcite is unaltered and generally free of inclusions. Exsolution is seen along the cleavage planes. Nepheline (15% modal abundance) is slightly smaller than the calcite grains, anhedral and shows alteration. Diopside (25% modal abundance) forms large euhedral to subhedral grains, reaching 8 mm in diameter. Diopside contains numerous apatite and calcite inclusions. Most of the apatite (5% modal abundance) is stubby, small (<0.1 mm) and anhedral to subhedral. The stubby apatite contains minimal inclusions and minimal fracturing (Figure B.4-B). Some apatite is prismatic, with calcite inclusions and moderate to low fracturing. These grains are found either cutting across other mineral phases or as an inclusion within minerals such as melanite. Similar to the diopside, melanite (25% modal abundance) forms large euhedral to subhedral grains, reaching 10 mm in diameter. The melanite contains numerous inclusions of apatite, calcite and pyroxene (Figure B.4- C). Fractures are few, but if present are filled with carbonate material.

Zoning: Apatite from the melanite ijolite is stubby and prismatic, and commonly contains calcite inclusions. The apatite typically contains two to three zones (Figure 7c). The zones are anhedral and divisions between the zones are gradual. The analyzed grains do not contain zones with resorption textures.

2001oka.AI.136 and 138: Apatite Okaite, Husereau Hill

Hand Sample: Samples 136 and 138 were obtained from a small outcrop within the Husereau Hill. This apatite okaite is a coarse-grained mafic rock, equigranular with a grain size that range from 1-3 mm in diameter. Prismatic euhedral apatite grains are abundant throughout the rock, and can reach up to 2 cm in length (Figure B.5-A). Most grains are present in radial clusters that can reach several cm in diameter.

Petrography: Minerals include anhedral melilite (45% modal abundance, ~2mm diameter), euhedral prismatic apatite (15-20% modal abundance, up to several mm in length), subhedral perovskite (5-10% modal abundance, ~1mm), euhedral to subhedral magnetite (5-10% modal abundance, ~1-2mm), subhedral to anhedral calcite (15% modal abundance, >2 mm) and subhedral to anhedral phlogopite (<5% modal abundance, <1mm in diameter). Large prismatic apatite is present as radial clusters or shows trachytic texture (Figure B.5-B). Smaller apatite grains are present within calcite minerals and are generally oriented in the same direction. Phlogopite forms anhedral to subhedral grains with some oxide inclusions. Smaller anhedral phlogopite is present as inclusions within the calcite and melilite grains. Subhedral to euhedral oxide (15-20% modal abundance) can reach several mm in diameter and is typically free of inclusions.

Zoning: Apatite grains were analyzed both in situ and as grain mounts. There are two phases of apatite growth within the apatite okaite. The primary phase is referred to as the “first-generation” of apatite. Zoning is best described when viewed as a basal section. The first-generation apatite typically contains four to five oscillatory zones. Sector zoning is also present in selected grains. The oscillatory zones display euhedral outlines

and the boundaries between the zones are abrupt. None of the zones displays resorption textures. Euhedral oscillatory zones vary between <5 to 10 μm in width (Figure B.5-C).

The second-generation apatite (*i.e.* the second phase of apatite growth) from the apatite okaite is located around the outer border or within fractures of the first-generation apatite. All grains show two to three anhedral zones. No correlation can be made among the zones within the second-generation apatite and there is no indication of resorption textures. The vein-like grains are small, averaging <50 μm in diameter. The zones within the grains are commonly <10 μm (Figure B.5-D).

2000oka.A3.120: Calcite Ijolite, St. Lawrence Mine

Hand Sample: Sample 120 contains a contact between a coarse-grained carbonatite and a calcite ijolite. The calcite ijolite was selected for analysis. The contact is irregular yet sharp between the two rock types. The carbonatite contains 90% leucocratic minerals (mostly calcite) and 10% mafic minerals (mostly phlogopite) (Figure B.6-A). Grains are subhedral to anhedral and can be up to 0.5 cm in diameter. The ijolite consists of 20-25% leucocratic minerals (nepheline and calcite) and 75-80% mafic minerals (pyroxene, phlogopite, oxides and others not identified).

Petrography: The contact between the carbonatite and ijolite is sharp and irregular. The carbonatite contains clean euhedral to subhedral grains, mostly leucocratic. Minerals include calcite (60% modal abundance), nepheline (15% modal abundance), apatite (<5% modal abundance), oxides (5% modal abundance) and phlogopite (10% modal abundance). Phlogopite is comparatively large in size (several millimeters in length),

unaltered and euhedral. Within the silicate rocks, patchy sections of alteration are present. For the most part, calcite (30% modal abundance) forms fresh anhedral grains, 1-2 mm in diameter and free of inclusions. Pyroxene (40% modal abundance) forms subhedral to euhedral grains 1-2 mm in length, is full of inclusions and is surrounded by altered material. Apatite (<5% modal abundance) is euhedral and forms prismatic grains 0.2-0.6 mm in length. Apatite is found mostly within grain boundaries, shows moderate to intense fracturing and typically contains carbonate inclusions. Nepheline (20% modal abundance) is subhedral to anhedral and <1mm in diameter, usually containing inclusions. Phlogopite (5%) forms subhedral grains that range from 0.1 to 1 mm in length. The phlogopite crystals are without inclusions and the boundaries are sharp and surrounded by altered material. Some grains are bent in shape and exhibits undulous extinction. Oxides (10%) are anhedral, 0.1 to 0.5 mm in diameter, and are present throughout the slide and as inclusions.

Zoning: Apatite grains were analyzed from the ijolitic segment of this sample. Two phases of apatite growth are present in the calcite ijolite. The primary phase, also referred to as the first-generation apatite, contains stubby and prismatic grains. The prismatic grains can reach 2 mm in length, are subhedral to euhedral, and contain numerous calcite inclusions. The BSE images of these grains do not show zonation (Figure B.6-Band C). The stubby apatite grains are euhedral to anhedral, small (<0.05 mm) and are located within or between other mineral phases. The first-generation stubby apatite also does not contain zonation on the BSE image. The second-generation apatite (*i.e.* the second phase of apatite crystallization) is anhedral, and located around the grain

boundaries or within fractures of the first-generation apatite. The second-generation apatite contains anhedral oscillatory and/or sector zoning (Figure B.6-D).

1997oka.A1.106 and 110: nepheline okaite, Husereau Hill

Hand Sample: Nepheline okaite was collected from Husereau Hill in 1997. The rocks are coarse-grained, equigranular (grains range from 2-4 mm in diameter) and contain about 60% leucocratic minerals and 40% mafic minerals (Figure B.7 A). Lighter coloured minerals include anhedral calcite, nepheline, and melilite. Mafic minerals include anhedral phlogopite and possibly some perovskite and magnetite, although it is difficult to identify them with the unaided eye.

Petrography: Calcite (10% modal abundance) is anhedral, usually without inclusions but some contain small apatite or oxides. The edges of most grains seem to show embayments. Some grains show signs of dolomitization. Phlogopite (15% modal abundance) is subhedral, typically without inclusions, unaltered and is pleochroic tan to green-brown. Apatite (5% modal abundance) forms stubby as well as prismatic euhedral crystals, range from 1-3 mm in length, and is commonly present as inclusions (Figure B.7 B). A higher percentage of stubby apatite is present in sample 110. Nepheline (25% modal abundance) is highly altered and peppered with inclusions of small micas and other minerals. Melilite (40% modal abundance) is also surrounded by altered material and contains numerous inclusions. Small anhedral pyroxene (<10% modal abundance) is also present. Sample 110 has a higher degree of alteration than sample 106.

Zoning: Within samples 106 and 110, apatite grains are mostly prismatic, up to several mm in length, yet certain grains are stubby with diameters averaging 0.2 mm. Grains are euhedral to subhedral with minimal fracturing and minimal calcite inclusions. All grains display some degree of zoning. The apatite typically possesses three or more subhedral oscillatory zones (Figure B.7 C). Some grains, however, contain complex sector zoning (Figure B.7 D). Apatite containing sector zoning are stubby and are typically found within sample 110. Borders between zones are abrupt.

The following samples were collected and processed by Dr. Keith Bell or Dr. Jianping Wen. No hand samples or thin sections were available, however separated grains were on hand. Hand sample and petrographic descriptions are quoted directly from the Dr. Bell's field notes and Wen's thesis (1985).

OC310: Medium grained calcite-carbonatite, St Lawrence Mine (Grain mounts only)

Hand Sample: Medium grained carbonatite. Surface stains dark brown.

Petrography: 90% calcite, up to 4mm in size, anhedral. Accessory olivine, colourless, high relief, high birefringence, anhedral to subhedral. Accessory phlogopite, up to 1 mm in size, anhedral to subhedral, pleochroic (yellow-brown). Some phlogopite is zoned. Accessory apatite, <0.5 in size, rounded. Accessory pyrochlore, <0.1 mm in size, anhedral to subhedral.

Zoning: Grains are stubby, euhedral to subhedral and range from 0.4 to 0.8 mm in length. Apatite typically includes large, rounded calcite inclusions, up to 0.1 mm in length. Grain edges are smooth and fracturing is minimal. Most apatite contains two or three subhedral oscillatory zones, whereas others do not show zoning in the BSE images. As these grains are viewed along the c-axis (in grain mounts), the zones cannot be correlated with other apatite. The boundaries between the zones are abrupt.

OC315: Layered Carbonatite, St. Lawrence Mine

Hand Sample: Layered Carbonatite. Medium-grained apatite-diopside-calcite-carbonatite. Collected from the wall of the north pit.

Petrography: 80% calcite, up to 3 mm in size, anhedral. 5% apatite, <0.5 mm in size, rounded and prismatic. Five percent phlogopite, up to 2 mm in size, anhedral to subhedral, pleochroic (brown green). Accessory pyrochlore, 0.5 mm in size, anhedral to subhedral.

Zoning: Apatite is stubby, subhedral, and ranges from 0.1 to 0.5mm in length. Calcite inclusions are rounded and very small. Fractures are minimal, and the apatite grain edges are irregular. Most grains do not show zoning in the BSE image. Only a few apatite grains show two zones. Borders between zones appear blurry/gradational. Difference in brightness between the two zones is very slight.

OC319: Coarse-grained carbonatite

Hand Sample: Very coarse-grained calcite with stubby green mineral. Collected on south face of the southerly pit at St. Lawrence Mine.

Petrography: Coarse-grained orthopyroxene-calcite-carbonatite; 60% calcite, up to 10 mm in size, anhedral. 35% orthopyroxene, up to 10mm in size, colourless, high relief, parallel extinction. Most orthopyroxene are intergrown with calcite. Accessory apatite, rounded or prismatic, up to 4 mm long.

Zoning: Apatite is stubby and prismatic reaching 0.5mm in diameter and >1mm in length. The grains are subhedral with calcite inclusions and minimal fracturing. Apatite typically contains two to three subhedral oscillatory zones up to 100 μm in thickness. There is only a slight variation in brightness on the BSE scale making the zones difficult to view. Boundaries between the zones are abrupt

Figure B.1: Samples 1986oka.A2.004 and 2000oka.A2.152: Niocalite carbonatite from the Bond Zone, Oka Carbonatite Complex. A: photograph of the hand sample, B: photograph of a thin section (Ct=calcite, Nc=niocalite, Ap=apatite), C and D: BSE images of apatite. Scale bars are located within each photograph.

Figure B.2: Sample 1986oka.A3.146: layered carbonatite from the St. Lawrence Mines, Oka Carbonatite Complex. A: photograph of the hand sample. B, C and D: BSE images of apatite. Scale bars are located within each photograph.

Figure B.3: Sample 1986oka.A3.124: monticellite carbonatite from the St. Lawrence Mines, Oka Carbonatite Complex. A: photograph of the hand sample, B: photograph of a thin section showing both stubby and elongate apatite grains surrounded by calcite and monticellite, C and D: BSE images of apatite. Scale bars are located within each photograph.

Figure B.4: Samples 1986oka.A4.089 : Melanite ijolite from the Nature Centre, Oka Carbonatite Complex. A: photograph of the hand sample. B and C: photograph of thin sections (Mt=melanite, Cb=carbonate, Dp=diopside, Ap=apatite). D: BSE images of apatite. Scale bars are located within each photograph.

Figure B.5: Sample 2001oka.A1.136 and 138: apatite-okaite from the Husereau Hills, Oka Carbonatite Complex. A: photograph of hand sample. Note the radial apatite clusters. B: is a photograph of a thin section showing trachytic prismatic apatite (Cb=carbonatite, MI=melilite, Ap=apatite). C and D: BSE images of apatite. C shows the optimum contrast for first-generation apatite, and D shows optimum contrast for the second-generation apatite. Scale bars are located within each photograph.

Figure B.6: Sample 1986oka.A1.120: calcic ijolite from the St. Lawrence Mines, Oka Carbonatite Complex. A: photograph of hand sample 120. This hand sample was removed from a contact between a coarse-grained carbonatite and an ijolite silicate rocks. The thin section was prepared from the ijolite portion of the sample. B, C and D: BSE images of apatite. Scale bars are located within each photograph. B and C are elongate apatite, and D is a stubby apatite. The first-generation apatite does not show zoning in the BSE image. Note the second-generation apatite seen as the bright regions around and within the first-generation grains.

Figure B.7: Sample 1986oka.A1.106 and 110: nepheline okaite from the Husereau Hills, Oka Carbonatite Complex. A: photograph of hand sample 110. B: is a photograph of a thin section showing both stubby and elongate apatite (Ct=calcite, MI=melilite, Ap=apatite, Ph=phlogopite, Pv=perovskite). The dark material consists of magnetite and altered material. C and D: BSE images of apatite. Scale bars are located within each photograph.

APPENDIX C

SAMPLE PREPARATION AND ANALYSIS

Carbonatite, ijolite and okaite samples were collected from Husereau Hill, the Nature Center, the Bond Zone and the two St. Lawrence Mine pits from the year 1985 to 2001 (Figure C.1). Thin sections were prepared from twenty samples for the purpose of petrographic, BSE images and microprobe analyses. Six samples were crushed and sorted after which the apatite grains were separated out by hand and placed into an epoxy mount. Detailed petrological analyses and SEM descriptions of the samples used in this study are located in Appendix B. A brief summary is given below in Table C.1 (HS = hand sample, TS = thin section, GM = grain mount):

Table C.1: List of samples used for this study along with the abbreviations, year collected and type of preparation. See Appendix B for a detailed description of each sample.

ROCK SERIES	ROCK TYPE	ABBREV.	LOCATION	YEAR	SMPL PREP
Carbonatite	Niocalite crb	NioCrb	Bond Zone	1985 and 2001	HS, TS
Carbonatite	Perovskite crb	PrvCrb	Bond Zone	2001	GM
Carbonatite	Layered crb	LayCrb	St. L. Mine	1985	GM
Carbonatite	Monticellite crb	MntCrb	St. L. Mine	1997	HS, TS
Carbonatite	Medium-grained	MedCrb	St. L. Mine	1985	GM
Carbonatite	Coarse-grained	CrsCrb	St. L. Mine	1985	GM
Carbonatite	Pegmatitic crb	PegCrb	St. L. Mine	2001	GM
Ijolite	Calcite ijolite	Cal-Ij	St. L. Mine	1997	HS, TS
Ijolite	Melanite ijolite	Mel-Ij	Nature Centre	1985	HS, TS
Okaite	Apatite okaite	ApOk	Husereau Hill	2000	HS, TS, GM
Okaite	Nepheline okaite	NphOk	Husereau Hill	1997	HS, TS

Backscattered electron photomicrographs were obtained from the scanning electron microscope (SEM) and electron microscope at Carleton University. The images were

contrast optimized 300- second scans on the JEOL 6400 SEM equipped with a JEOL solid-state, backscattered electron detector. The backscatter images reveal zoning not visible in transmitted light. Zones are identified on the basis of brightness.

The electron microprobe used was a Camebax MBX Electron Microprobe equipped with four WDX X-ray Spectrometers. Samples and standards were coated with 200 angstroms of carbon and analyzed by wavelength dispersive X-ray analyses (WDX). A 15kV, 15nA electron beam was used for a raster area of 5x5 to 10x10 microns. The natural and synthetic standards used for instrument calibration are listed in Table C.1. Counting times varied from 30 to 120 seconds or 40,000 counts, depending on the element. Table C.2 lists the counting time, as well as the minimum detection limit (MDL) for each element. For example, the rare-earth elements La → Sm were analyzed with counting times from 80 to 100 seconds. The La and Ce analyses from the Oka apatites are both well above the MDL. However, data from remaining LREEs, (Pr, Nd and Sm) are below the MDL. Raw X-ray data were converted to elemental weight % by the Cameca PAP matrix correction program. Analyses are accurate to 1-2% relative for major elements at >5 wt%, 3-10% relative for major elements at 0.1–5 wt%. Relative error approaches 100% for trace elements (<0.1 wt%) as MDL is approached (see Table C.3). The data results from the electron microprobe analyses on the Oka apatite are listed in Table C.4

Figure C.1: Geological map of the Oka Carbonatite Complex, Quebec. The samples were collected from four areas within the Oka Complex. Thin section photographs show examples of apatite within each of the various rock types studied. Scale bar is located within each photograph.

Table C.2: List of the natural and synthetic standards used for the electron microprobe instrument calibration and test measurements.

Element	Line 15kV	Standard	Type
F	Ka	Durango apatite	USNM
P	Ka	Durango apatite	USNM
Ca	Ka	Durango apatite	USNM
Mn	Ka	MnTiO ₃	syn
Na	Ka	Tugtupite	natural
Cl	Ka	Tugtupite	natural
Ce	La	CeO ₂	syn
Nd	La	NdAlO ₃	syn
Sr	La	Celestite	natural
S	Ka	Celestite	natural
La	La	LaAlO ₃	syn
Fe	Ka	Y ₃ Fe ₅ O ₁₂	syn
Si	Ka	Tugtupite	natural
Y	La	Y ₃ Fe ₅ O ₁₂	syn
Sm	Lb	SmAlO ₃	syn
Pr	Lb	PrF ₃	syn
Ba	La	BaFe ₈ O ₉	syn
As	La	NiAs	natural

Table C.3: Table listing the peak and background data combined with counting time for error and minimum detection limit (MDL) calculations for the elements analyzed during the electron microprobe analyses.

LLD= (2*√(2))/(m * (√ (Rb/T)))								
where m = (Rp-Rb)/concentration				P + B			MDL	
Element-ox wt %	conc	peak cps	bkg cps	Time total	m	√(Rb/T)	LLD Wt%	LLD ppm
F-apatite	3.56	27.47	1.68	120	7.24	0.12	0.046	462
F-apatite	1.61	18.05	1.55	120	10.25	0.11	0.031	314
Cl-apatite	0.37	21.07	3.40	40	47.76	0.29	0.017	173
Ce	2.37	132.5	27.00	80	44.51	0.58	0.037	369
Ce-Durango	0.55	47.65	25.85	80	39.64	0.57	0.041	406
La-Durango	0.49	43.83	22.25	80	44.04	0.53	0.034	339
Pr	0.22	37.46	32.78	100	21.27	0.57	0.076	762
Nd	0.15	3.60	2.70	100	6.00	0.16	0.078	775
Nd	0.83	12.70	4.65	100	9.70	0.22	0.063	629
Sm	0.07	4.7	4.32	100	5.43	0.21	0.108	1084
Sr	0.81	99.87	37.50	40	77.00	0.97	0.036	356
Y	0.13	2.65	1.60	40	8.08	0.20	0.070	701
Mn	0.14	8.20	4.07	30	29.50	0.37	0.035	353
Fe	0.08	6.40	4.40	30	25.00	0.38	0.043	434
Si-apatite	2.16	313.93	46.00	60	124.04	0.88	0.020	200
Si-Durango	0.29	69.94	34.00	30	123.93	1.06	0.024	243
Na-Durango	0.29	33.47	12.00	30	74.03	0.63	0.024	242
As in apatite	0.15	21.47	18.00	40	23.13	0.67	0.082	821

Table C.4: Composition in of apatite grains by electron microprobe analyses for different rock types from the Oka carbonatite complex (in wt%). A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P2O5	SiO2	As2O5	SO3	CaO	Na2O	FeO	MnO	SrO
A2 Niocalite-Carbonatite 152										
1	152-001	35.64	3.42	0.00	0.16	51.08	0.09	0.02	0.13	0.90
	152-002	34.15	4.05	0.04	0.32	49.83	0.10	0.00	0.10	0.91
2	152-003	34.92	3.52	0.03	0.19	51.10	0.11	0.01	0.02	0.85
	152-004	33.48	3.88	0.00	0.21	50.58	0.07	0.00	0.02	0.90
3	152-005	35.07	3.54	0.03	0.21	51.00	0.10	0.00	0.04	0.88
	152-006	33.55	4.47	0.00	0.21	49.15	0.12	0.00	0.16	0.88
4	152-007	34.21	3.91	0.00	0.28	50.76	0.15	0.00	0.10	0.84
	152-008	33.38	4.55	0.00	0.22	49.41	0.08	0.00	0.15	0.95
	Average	34.34	3.84	0.01	0.23	49.56	0.10	0.00	0.09	0.89
A2 Niocalite-Carbonatite 004										
1	004-1	34.50	3.58	0.01	0.26	50.58	0.12	0.00	0.08	0.88
	004-2	35.68	3.27	0.00	0.31	51.36	0.08	0.03	0.10	0.97
2	004-3	34.47	3.39	0.00	0.32	50.98	0.11	0.00	0.00	1.00
	004-4	33.12	4.18	0.01	0.31	49.97	0.14	0.00	0.07	0.99
3	004-5	33.50	3.98	0.00	0.26	49.39	0.01	0.00	0.03	0.93
	004-6	34.88	3.50	0.02	0.28	50.33	0.07	0.00	0.10	0.93
	004-7	34.83	3.19	0.03	0.28	50.93	0.11	0.00	0.09	0.97
	004-8	33.81	3.81	0.00	0.35	50.48	0.08	0.00	0.05	0.89
	004-9	34.74	3.51	0.00	0.27	51.05	0.12	0.10	0.14	0.99
4	004-10	35.20	3.33	0.03	0.26	50.81	0.08	0.00	0.08	0.93
	004-11	34.25	3.60	0.00	0.25	50.49	0.09	0.03	0.06	0.92
	004-12	34.67	3.39	0.05	0.25	50.84	0.09	0.00	0.04	0.96
	004-13	34.08	3.88	0.00	0.25	50.47	0.10	0.01	0.08	0.97
	004-14	34.68	3.47	0.03	0.26	50.38	0.08	0.01	0.04	0.88
	Average	34.46	3.58	0.01	0.28	50.58	0.09	0.01	0.07	0.94
A2 Perovskite-Carbonatite 146										
1	146-66	36.60	2.16	0.01	0.03	50.28	0.11	0.07	0.05	0.75
	146-67	36.26	2.44	0.00	0.16	50.53	0.04	0.00	0.02	0.87
	146-68	34.78	2.77	0.03	0.37	50.62	0.16	0.00	0.02	0.73
2	146-69	35.93	2.04	0.00	0.07	50.90	0.09	0.00	0.03	0.80
	146-70	36.26	2.19	0.03	0.22	50.48	0.15	0.01	0.00	0.76
	146-71	35.77	2.62	0.00	0.30	51.15	0.11	0.00	0.01	0.76
3	146-72	35.83	2.33	0.00	0.20	50.78	0.15	0.00	0.06	0.79
	146-73	35.99	2.52	0.03	0.23	50.33	0.09	0.00	0.00	0.83
	Average	35.93	2.38	0.01	0.20	50.63	0.11	0.01	0.02	0.79

Table C.4: Composition (continued):

GRAIN	SAMPLE	BaO	Y2O3	La2O3	Ce2O3	Pr2O3	Nd2O3	Sm2O3	F	Cl	TOTAL	TOT-O
A2 Nicalite-Carbonatite 152												
1	152-001	0.00	0.00	1.51	3.24	0.19	0.78	0.14	1.29	0.00	98.59	98.03
	152-002	0.00	0.08	2.02	4.00	0.12	1.08	0.11	1.23	0.03	98.17	97.65
2	152-003	0.02	0.02	1.79	3.32	0.30	0.95	0.12	1.23	0.01	98.51	97.99
	152-004	0.02	0.13	2.02	4.15	0.20	1.00	0.00	1.26	0.00	97.92	97.39
3	152-005	0.00	0.13	1.58	3.24	0.14	0.80	0.08	1.33	0.02	98.19	97.63
	152-006	0.06	0.16	2.13	4.27	0.34	1.10	0.05	1.46	0.01	98.12	97.50
4	152-007	0.06	0.04	1.70	3.40	0.14	1.01	0.14	1.24	0.03	98.01	97.48
	152-008	0.00	0.13	2.23	4.35	0.14	1.04	0.25	1.24	0.02	98.14	97.61
	Average	0.02	0.08	1.82	3.61	0.19	0.98	0.11	1.28	0.02	97.16	96.62
A2 Nicalite-Carbonatite 004												
1	004-1	0.04	0.00	1.61	2.94	0.10	0.82	0.00	1.13	0.03	96.68	96.20
	004-2	0.03	0.07	1.47	2.57	0.18	0.77	0.07	1.26	0.04	98.26	97.72
2	004-3	0.00	0.06	1.39	2.66	0.12	0.65	0.11	1.34	0.02	96.62	96.05
	004-4	0.04	0.05	2.01	3.60	0.17	0.93	0.00	1.45	0.04	97.08	96.46
3	004-5	0.00	0.01	2.14	3.79	0.09	0.85	0.03	1.43	0.03	96.47	95.86
	004-6	0.03	0.04	1.62	2.95	0.07	0.90	0.07	1.38	0.03	97.20	96.61
	004-7	0.08	0.06	1.42	2.61	0.15	0.76	0.04	1.40	0.03	96.98	96.38
	004-8	0.00	0.00	1.65	3.13	0.10	0.77	0.16	1.39	0.03	96.70	96.11
	004-9	0.00	0.02	1.40	2.74	0.08	0.96	0.10	1.29	0.04	97.55	97.00
4	004-10	0.01	0.00	1.60	3.01	0.09	0.72	0.18	1.44	0.02	97.79	97.18
	004-11	0.04	0.04	1.75	3.30	0.14	0.91	0.16	1.47	0.03	97.53	96.90
	004-12	0.00	0.01	1.52	2.90	0.13	0.90	0.22	1.47	0.01	97.45	96.83
	004-13	0.01	0.07	1.83	3.36	0.26	0.96	0.00	1.42	0.03	97.78	97.18
	004-14	0.02	0.03	1.95	3.31	0.10	0.91	0.09	1.45	0.04	97.73	97.11
	Average	0.02	0.03	1.67	3.06	0.13	0.84	0.09	1.38	0.03	97.27	96.69
A2 Perovskite-Carbonatite 146												
1	146-66	0.00	0.13	1.27	2.31	0.15	0.71	0.00	1.45	0.02	96.10	95.48
	146-67	0.05	0.09	1.20	2.29	0.07	0.59	0.21	1.72	0.03	96.57	95.84
	146-68	0.00	0.15	1.08	2.02	0.12	0.76	0.11	1.85	0.02	95.59	94.81
2	146-69	0.03	0.16	1.19	2.28	0.19	0.67	0.01	1.74	0.02	96.15	95.41
	146-70	0.00	0.12	1.17	2.19	0.12	0.67	0.00	2.02	0.01	96.31	95.46
	146-71	0.03	0.16	1.15	2.20	0.09	0.60	0.10	1.77	0.03	96.85	96.10
3	146-72	0.05	0.07	1.08	2.21	0.11	0.52	0.21	1.51	0.02	95.92	95.28
	146-73	0.07	0.12	1.21	2.29	0.20	0.69	0.09	2.21	0.01	96.91	95.98
	Average	0.03	0.11	1.17	2.22	0.13	0.65	0.09	1.78	0.02	96.30	95.55

Table C.4: Atoms per formula unit. Formulae based a charge of 50. A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P	SI	AS	S	SUBT	CA	NA	FE	MN	SR
A2 Niocalite-Carbonatite 152											
1	152-001	5.34	0.60	0.00	0.02	5.96	9.68	0.03	0.00	0.02	0.09
	152-002	5.19	0.73	0.00	0.04	5.96	9.58	0.03	0.00	0.02	0.10
2	152-003	5.27	0.63	0.00	0.03	5.92	9.75	0.04	0.00	0.00	0.09
	152-004	5.13	0.70	0.00	0.03	5.86	9.82	0.03	0.00	0.00	0.10
3	152-005	5.29	0.63	0.00	0.03	5.95	9.73	0.03	0.00	0.01	0.09
	152-006	5.13	0.81	0.00	0.03	5.97	9.52	0.04	0.00	0.02	0.09
	152-007	5.19	0.70	0.00	0.04	5.93	9.75	0.05	0.00	0.02	0.09
4	152-008	5.10	0.82	0.00	0.03	5.96	9.56	0.03	0.00	0.02	0.10
	Average	5.25	0.69	0.00	0.03	5.98	9.58	0.04	0.00	0.01	0.09
A2 Niocalite-Carbonatite 004											
1	004-1	5.27	0.65	0.00	0.04	5.95	9.77	0.04	0.00	0.01	0.09
	004-2	5.34	0.58	0.00	0.04	5.96	9.73	0.03	0.00	0.01	0.10
2	004-3	5.27	0.61	0.00	0.04	5.92	9.86	0.04	0.00	0.00	0.10
	004-4	5.11	0.76	0.00	0.04	5.91	9.75	0.05	0.00	0.01	0.11
	004-5	5.19	0.73	0.00	0.04	5.95	9.68	0.00	0.00	0.01	0.10
	004-6	5.30	0.63	0.00	0.04	5.97	9.68	0.02	0.00	0.02	0.10
3	004-7	5.31	0.57	0.00	0.04	5.92	9.82	0.04	0.00	0.01	0.10
	004-8	5.19	0.69	0.00	0.05	5.93	9.81	0.03	0.00	0.01	0.09
	004-9	5.27	0.63	0.00	0.04	5.93	9.79	0.04	0.02	0.02	0.10
	004-10	5.32	0.60	0.00	0.04	5.96	9.72	0.03	0.00	0.01	0.10
	004-11	5.23	0.65	0.00	0.04	5.92	9.76	0.03	0.01	0.01	0.10
4	004-12	5.28	0.61	0.01	0.03	5.93	9.79	0.03	0.00	0.01	0.10
	004-13	5.20	0.70	0.00	0.03	5.93	9.74	0.04	0.00	0.01	0.10
	004-14	5.28	0.62	0.00	0.04	5.94	9.70	0.03	0.00	0.01	0.09
	Average	5.25	0.64	0.00	0.04	5.94	9.76	0.03	0.00	0.01	0.10
A2 Perovskite-Carbonatite 146											
	146-66	5.58	0.39	0.00	0.00	5.97	9.69	0.04	0.01	0.01	0.08
1	146-67	5.52	0.44	0.00	0.02	5.97	9.73	0.02	0.00	0.00	0.09
	146-68	5.37	0.51	0.00	0.05	5.92	9.88	0.06	0.00	0.00	0.08
	146-69	5.51	0.37	0.00	0.01	5.89	9.88	0.03	0.00	0.00	0.08
2	146-70	5.54	0.40	0.00	0.03	5.96	9.75	0.05	0.00	0.00	0.08
	146-71	5.43	0.47	0.00	0.04	5.94	9.83	0.04	0.00	0.00	0.08
	146-72	5.48	0.42	0.00	0.03	5.93	9.83	0.05	0.00	0.01	0.08
3	146-73	5.49	0.45	0.00	0.03	5.97	9.71	0.03	0.00	0.00	0.09
	Average	5.49	0.43	0.00	0.03	5.95	9.79	0.04	0.00	0.00	0.08

Table C.4 Atoms (continued):

GRAIN	SAMPLE	EA	Y	LA	CE	PR	ND	SM	SUBT	OH	F	CL	SUBT
A2 Niocalite-Carbonatite 152													
1	152-001	0.00	0.00	0.10	0.21	0.01	0.05	0.01	10.21	1.28	0.72	0.00	0.72
	152-002	0.00	0.01	0.13	0.26	0.01	0.07	0.01	10.22	1.29	0.70	0.01	0.71
2	152-003	0.00	0.00	0.12	0.22	0.02	0.06	0.01	10.31	1.30	0.70	0.00	0.70
	152-004	0.00	0.01	0.14	0.28	0.01	0.07	0.00	10.44	1.28	0.72	0.00	0.72
3	152-005	0.00	0.01	0.10	0.21	0.01	0.05	0.01	10.25	1.25	0.75	0.01	0.75
	152-006	0.01	0.02	0.14	0.28	0.02	0.07	0.00	10.22	1.16	0.83	0.00	0.84
4	152-007	0.00	0.00	0.11	0.22	0.01	0.07	0.01	10.32	1.29	0.70	0.01	0.71
	152-008	0.00	0.01	0.15	0.29	0.01	0.07	0.02	10.25	1.29	0.71	0.01	0.71
	Average	0.00	0.01	0.12	0.24	0.01	0.06	0.01	10.18	1.26	0.73	0.00	0.74
A2 Niocalite-Carbonatite 004													
1	004-1	0.00	0.00	0.11	0.19	0.01	0.05	0.00	10.28	1.35	0.64	0.01	0.65
	004-2	0.00	0.01	0.10	0.17	0.01	0.05	0.01	10.21	1.29	0.70	0.01	0.71
2	004-3	0.00	0.01	0.09	0.18	0.01	0.04	0.01	10.33	1.23	0.77	0.01	0.77
	004-4	0.00	0.01	0.14	0.24	0.01	0.06	0.00	10.37	1.15	0.84	0.01	0.85
3	004-5	0.00	0.00	0.14	0.25	0.01	0.06	0.00	10.25	1.17	0.83	0.01	0.83
	004-6	0.00	0.00	0.11	0.19	0.00	0.06	0.01	10.19	1.21	0.78	0.01	0.79
	004-7	0.01	0.01	0.09	0.17	0.01	0.05	0.00	10.31	1.19	0.80	0.01	0.81
	004-8	0.00	0.00	0.11	0.21	0.01	0.05	0.01	10.32	1.20	0.80	0.01	0.81
	004-9	0.00	0.00	0.09	0.18	0.01	0.06	0.01	10.32	1.26	0.73	0.01	0.74
4	004-10	0.00	0.00	0.11	0.20	0.01	0.05	0.01	10.23	1.18	0.81	0.01	0.82
	004-11	0.00	0.00	0.12	0.22	0.01	0.06	0.01	10.33	1.16	0.84	0.01	0.85
	004-12	0.00	0.00	0.10	0.19	0.01	0.06	0.01	10.31	1.16	0.84	0.00	0.84
	004-13	0.00	0.01	0.12	0.22	0.02	0.06	0.00	10.32	1.18	0.81	0.01	0.82
	004-14	0.00	0.00	0.13	0.22	0.01	0.06	0.01	10.25	1.17	0.82	0.01	0.84
	Average	0.00	0.00	0.11	0.20	0.01	0.05	0.01	10.29	1.21	0.79	0.01	0.79
A2 Perovskite-Carbonatite 146													
1	146-66	0.00	0.01	0.09	0.15	0.01	0.05	0.00	10.13	1.17	0.82	0.01	0.83
	146-67	0.00	0.01	0.08	0.15	0.00	0.04	0.01	10.13	1.01	0.98	0.01	0.99
	146-68	0.00	0.01	0.07	0.14	0.01	0.05	0.01	10.30	0.93	1.07	0.01	1.07
2	146-69	0.00	0.02	0.08	0.15	0.01	0.04	0.00	10.31	1.00	1.00	0.01	1.00
	146-70	0.00	0.00	0.08	0.15	0.01	0.04	0.00	10.16	0.85	1.15	0.01	1.16
	146-71	0.00	0.02	0.08	0.15	0.01	0.04	0.01	10.24	0.99	1.00	0.01	1.01
3	146-72	0.00	0.01	0.07	0.15	0.01	0.03	0.01	10.26	1.13	0.86	0.01	0.87
	146-73	0.01	0.01	0.08	0.15	0.01	0.05	0.01	10.14	0.74	1.26	0.00	1.26
	Average	0.00	0.01	0.08	0.15	0.01	0.04	0.01	10.21	0.98	1.02	0.01	1.02

Table C.4: Composition in of apatite grains by electron microprobe analyses for different rock types from the Oka carbonatite complex (in wt%). A1=

Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P2O5	SiO2	As2O5	SO3	CaO	Na2O	FeO	MnO	SrO
A3 Monticellite-Carbonatite 124										
1	124-35	37.85	1.90	0.03	0.21	51.54	0.03	0.05	0.05	0.75
	124-36	37.63	2.16	0.03	0.12	52.12	0.04	0.05	0.01	0.69
	124-37	37.47	1.98	0.00	0.30	51.45	0.03	0.00	0.03	0.70
2	124-38	37.40	1.84	0.04	0.32	52.31	0.06	0.03	0.05	0.62
	124-39	37.70	1.74	0.01	0.19	51.79	0.06	0.04	0.03	0.69
	124-40	37.75	2.02	0.00	0.25	51.47	0.01	0.03	0.11	0.61
	124-41	37.52	1.85	0.00	0.41	52.66	0.09	0.08	0.14	0.61
	Average	37.62	1.93	0.02	0.26	51.91	0.05	0.04	0.06	0.67
1	315-42	36.74	2.29	0.03	0.18	49.50	0.08	0.00	0.04	0.90
	315-43	35.62	2.49	0.02	0.26	49.68	0.10	0.00	0.04	0.76
2	315-44	35.67	2.59	0.02	0.27	49.03	0.09	0.00	0.01	0.80
	315-45	35.79	2.62	0.01	0.26	49.31	0.13	0.00	0.09	0.82
3	315-46	35.73	2.40	0.00	0.22	48.95	0.11	0.00	0.08	0.71
	315-47	35.35	2.64	0.05	0.25	49.47	0.12	0.02	0.00	0.78
4	315-48	35.58	2.92	0.00	0.35	49.95	0.14	0.00	0.15	0.81
	315-49	36.74	2.37	0.05	0.24	49.75	0.08	0.00	0.03	0.82
	Average	35.90	2.54	0.02	0.25	49.46	0.11	0.00	0.06	0.80
A3 Medium-grained-carbonatite 310										
1	310-50	40.84	0.46	0.03	0.14	52.97	0.17	0.02	0.12	0.93
	310-51	40.46	0.58	0.00	0.14	53.17	0.21	0.00	0.10	0.89
2	310-52	39.60	0.97	0.04	0.12	52.50	0.17	0.00	0.03	0.80
	310-53	39.57	0.96	0.05	0.09	51.94	0.21	0.02	0.08	0.74
3	310-54	39.77	0.86	0.00	0.12	52.77	0.09	0.01	0.07	0.84
	310-55	39.28	0.61	0.00	0.07	52.21	0.19	0.02	0.07	0.85
	Average	39.92	0.74	0.02	0.11	52.59	0.17	0.01	0.08	0.84
A3 Pegmatitic-Carbonatite Grain mount 092										
1	092-56	37.53	1.37	0.01	0.14	50.83	0.26	0.02	0.04	0.90
	092-57	36.08	1.86	0.00	0.19	50.88	0.13	0.01	0.10	0.84
2	092-58	39.33	0.17	0.00	0.01	51.93	0.34	0.00	0.04	0.87
	092-59	38.74	0.85	0.00	0.10	51.90	0.21	0.04	0.16	0.78
	092-60	39.78	0.17	0.01	0.00	52.49	0.22	0.00	0.07	0.88
3	092-61	38.45	0.98	0.05	0.14	51.56	0.27	0.00	0.08	0.75
	092-62	39.13	1.10	0.00	0.12	51.33	0.24	0.02	0.14	0.78
4	092-63	39.03	0.44	0.00	0.01	51.96	0.34	0.02	0.10	0.84
	092-64	38.42	0.90	0.03	0.05	52.12	0.17	0.00	0.03	0.87
	092-65	39.97	0.27	0.03	0.08	52.72	0.28	0.00	0.05	0.98
	Average	38.65	0.81	0.01	0.08	51.77	0.25	0.01	0.08	0.85

Table C.4: Composition (continued):

GRAIN	SAMPLE	BaO	Y2O3	La2O3	Ce2O3	Pr2O3	Nd2O3	Sm2O3	F	Cl	TOTAL	TOT-O
A3 Monticellite-Carbonatite 124												
1	124-35	0.05	0.16	1.13	2.10	0.22	0.54	0.15	1.29	0.03	98.08	97.53
	124-36	0.03	0.18	1.31	2.37	0.26	0.66	0.06	1.31	0.01	99.04	98.49
2	124-37	0.04	0.16	0.92	1.65	0.09	0.43	0.15	1.51	0.00	96.91	96.27
	124-38	0.00	0.09	0.87	1.50	0.00	0.46	0.00	1.33	0.01	96.93	96.37
	124-39	0.05	0.10	0.96	1.77	0.14	0.45	0.12	1.29	0.02	97.15	96.60
	124-40	0.00	0.18	1.14	2.11	0.18	0.50	0.12	1.40	0.01	97.89	97.30
124-41		0.04	0.13	0.61	1.07	0.05	0.36	0.00	1.21	0.00	96.83	96.32
	Average	0.03	0.14	0.99	1.80	0.13	0.49	0.09	1.33	0.01	97.55	96.96
A3 Layered-Carbonatite 315												
1	315-42	0.00	0.15	1.67	2.78	0.10	0.93	0.14	1.67	0.04	97.24	96.53
	315-43	0.00	0.13	1.27	2.50	0.16	0.94	0.16	1.56	0.03	95.72	95.06
2	315-44	0.00	0.12	1.43	2.72	0.29	0.93	0.15	1.57	0.01	95.70	95.04
	315-45	0.00	0.20	1.62	2.85	0.33	1.07	0.07	1.55	0.03	96.75	96.09
3	315-46	0.00	0.12	1.33	2.30	0.16	0.84	0.04	1.56	0.02	94.57	93.91
	315-47	0.03	0.11	1.33	2.52	0.27	0.86	0.02	1.53	0.02	95.37	94.72
4	315-48	0.00	0.09	1.70	3.09	0.22	0.83	0.00	1.61	0.01	97.45	96.77
	315-49	0.01	0.19	1.39	2.78	0.24	0.77	0.17	1.58	0.00	97.21	96.54
Average		0.01	0.14	1.47	2.69	0.22	0.90	0.09	1.58	0.02	96.25	95.58
A3 Medium-grained-carbonatite 310												
1	310-50	0.04	0.04	0.55	0.82	0.03	0.25	0.00	1.77	0.01	99.19	98.44
	310-51	0.00	0.01	0.52	0.80	0.03	0.23	0.00	1.91	0.03	99.08	98.27
2	310-52	0.00	0.08	0.65	0.94	0.00	0.27	0.04	1.77	0.04	98.02	97.27
	310-53	0.00	0.04	0.69	1.10	0.11	0.31	0.06	1.69	0.03	97.69	96.97
3	310-54	0.00	0.00	0.53	0.85	0.05	0.24	0.12	1.73	0.00	98.05	97.32
	310-55	0.00	0.10	0.52	0.78	0.05	0.27	0.00	1.57	0.03	96.62	95.95
Average		0.01	0.05	0.58	0.88	0.05	0.26	0.04	1.74	0.02	98.11	97.37
A3 Pegmatitic-Carbonatite Grain mount 092												
1	092-56	0.00	0.11	1.01	1.74	0.11	0.51	0.00	1.74	0.00	96.32	95.59
	092-57	0.00	0.20	1.04	1.72	0.26	0.61	0.00	2.13	0.00	96.05	95.15
2	092-58	0.03	0.00	0.35	0.62	0.03	0.18	0.07	2.32	0.01	96.30	95.32
	092-59	0.00	0.17	0.64	1.10	0.07	0.37	0.01	2.16	0.01	97.31	96.40
3	092-60	0.01	0.08	0.33	0.67	0.09	0.25	0.14	2.08	0.05	97.32	96.43
	092-61	0.06	0.02	0.66	1.25	0.01	0.49	0.00	2.20	0.04	97.01	96.07
4	092-62	0.00	0.02	0.71	1.18	0.00	0.33	0.07	2.08	0.02	97.27	96.39
	092-63	0.00	0.06	0.44	0.84	0.08	0.32	0.06	2.17	0.02	96.73	95.81
092-64		0.04	0.09	0.57	1.03	0.10	0.31	0.05	2.63	0.02	97.43	96.32
	092-65	0.01	0.15	0.34	0.72	0.00	0.09	0.00	1.95	0.02	97.66	96.83
Average		0.02	0.09	0.61	1.09	0.08	0.35	0.04	2.15	0.02	96.94	96.03

Table C.4: Atoms per formula unit. Formulae based a charge of 50. A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P	SI	AS	S	SUBT	CA	NA	FE	MN	SR
A3 Monticellite-Carbonatite 124											
1	124-35	5.62	0.33	0.00	0.03	5.98	9.68	0.01	0.01	0.01	0.08
	124-36	5.56	0.38	0.00	0.02	5.95	9.74	0.01	0.01	0.00	0.07
	124-37	5.61	0.35	0.00	0.04	6.00	9.74	0.01	0.00	0.00	0.07
	124-38	5.59	0.32	0.00	0.04	5.95	9.89	0.02	0.01	0.01	0.06
2	124-39	5.63	0.31	0.00	0.02	5.96	9.79	0.02	0.01	0.00	0.07
	124-40	5.61	0.35	0.00	0.03	5.99	9.68	0.00	0.00	0.02	0.06
	124-41	5.58	0.33	0.00	0.06	5.96	9.91	0.03	0.01	0.02	0.06
	Average	5.60	0.34	0.00	0.03	5.97	9.77	0.02	0.01	0.01	0.07
A3 Layered-Carbonatite 315											
1	315-42	5.57	0.41	0.00	0.02	6.01	9.49	0.03	0.00	0.01	0.09
	315-43	5.48	0.45	0.00	0.04	5.97	9.67	0.04	0.00	0.01	0.08
	315-44	5.49	0.47	0.00	0.04	6.00	9.55	0.03	0.00	0.00	0.08
	315-45	5.47	0.47	0.00	0.04	5.98	9.54	0.05	0.00	0.01	0.09
3	315-46	5.54	0.44	0.00	0.03	6.01	9.60	0.04	0.00	0.01	0.08
	315-47	5.46	0.48	0.01	0.04	5.98	9.66	0.04	0.00	0.00	0.08
	315-48	5.40	0.52	0.00	0.05	5.97	9.60	0.05	0.00	0.02	0.08
	315-49	5.55	0.42	0.00	0.03	6.01	9.51	0.03	0.00	0.00	0.09
	Average	5.49	0.46	0.00	0.03	5.99	9.58	0.04	0.00	0.01	0.08
A3 Medium-grained-carbonatite 310											
1	310-50	5.91	0.08	0.00	0.02	6.01	9.70	0.06	0.00	0.02	0.09
	310-51	5.88	0.10	0.00	0.02	5.99	9.77	0.07	0.00	0.02	0.09
	310-52	5.82	0.17	0.00	0.02	6.00	9.76	0.06	0.00	0.01	0.08
	310-53	5.83	0.17	0.01	0.01	6.02	9.69	0.07	0.00	0.01	0.08
3	310-54	5.83	0.15	0.00	0.02	6.00	9.79	0.03	0.00	0.01	0.09
	310-55	5.85	0.11	0.00	0.01	5.97	9.84	0.07	0.00	0.01	0.09
	Average	5.85	0.13	0.00	0.01	6.00	9.76	0.06	0.00	0.01	0.08
A3 Pegmatite-Carbonatite Grain mount 092											
1	092-56	5.68	0.25	0.00	0.02	5.95	9.75	0.09	0.00	0.01	0.09
	092-57	5.54	0.34	0.00	0.03	5.90	9.89	0.05	0.00	0.02	0.09
	092-58	5.91	0.03	0.00	0.00	5.94	9.88	0.12	0.00	0.01	0.09
	092-59	5.79	0.15	0.00	0.01	5.95	9.81	0.07	0.01	0.02	0.08
3	092-60	5.91	0.03	0.00	0.00	5.94	9.87	0.08	0.00	0.01	0.09
	092-61	5.77	0.17	0.00	0.02	5.96	9.79	0.09	0.00	0.01	0.08
	092-62	5.82	0.19	0.00	0.02	6.03	9.66	0.08	0.00	0.02	0.08
	092-63	5.85	0.08	0.00	0.00	5.93	9.86	0.12	0.00	0.02	0.09
4	092-64	5.77	0.16	0.00	0.01	5.94	9.90	0.06	0.00	0.00	0.09
	092-65	5.90	0.05	0.00	0.01	5.96	9.84	0.10	0.00	0.01	0.10
	Average	5.79	0.14	0.00	0.01	5.95	9.82	0.08	0.00	0.01	0.09

Table C.4 Atoms (continued):

GRAIN	SAMPLE	BA	Y	LA	CE	PR	ND	SM	SUBT	OH	F	CL	SURT
A3 Monticellite-Carbonatite 124													
1	124-35	0.00	0.02	0.07	0.14	0.01	0.03	0.01	10.06	1.28	0.72	0.01	0.72
	124-36	0.00	0.02	0.08	0.15	0.02	0.04	0.00	10.15	1.28	0.72	0.00	0.72
	124-37	0.00	0.02	0.06	0.11	0.01	0.03	0.01	10.06	1.15	0.85	0.00	0.85
	124-38	0.00	0.01	0.06	0.10	0.00	0.03	0.00	10.17	1.25	0.74	0.00	0.75
2	124-39	0.00	0.01	0.06	0.11	0.01	0.03	0.01	10.13	1.28	0.72	0.01	0.73
	124-40	0.00	0.02	0.07	0.14	0.01	0.03	0.01	10.04	1.22	0.78	0.00	0.78
	124-41	0.00	0.01	0.04	0.07	0.00	0.02	0.00	10.18	1.33	0.67	0.00	0.67
	Average	0.00	0.01	0.06	0.12	0.01	0.03	0.01	10.11	1.26	0.74	0.00	0.74
A3 Layered-Carbonatite 315													
1	315-42	0.00	0.01	0.11	0.18	0.01	0.06	0.01	10.00	1.04	0.94	0.01	0.96
	315-43	0.00	0.01	0.09	0.17	0.01	0.06	0.01	10.14	1.10	0.90	0.01	0.90
	315-44	0.00	0.01	0.10	0.18	0.02	0.06	0.01	10.04	1.10	0.90	0.01	0.91
	315-45	0.00	0.02	0.11	0.19	0.02	0.07	0.00	10.09	1.11	0.88	0.01	0.90
3	315-46	0.00	0.01	0.09	0.15	0.01	0.06	0.00	10.05	1.09	0.90	0.01	0.91
	315-47	0.00	0.01	0.09	0.17	0.02	0.06	0.00	10.13	1.11	0.88	0.01	0.89
	315-48	0.00	0.01	0.11	0.20	0.02	0.05	0.00	10.14	1.09	0.91	0.00	0.91
	315-49	0.00	0.02	0.09	0.18	0.02	0.05	0.01	10.00	1.11	0.89	0.00	0.89
	Average	0.00	0.01	0.10	0.18	0.01	0.06	0.01	10.07	1.09	0.90	0.01	0.91
A3 Medium-grained-carbonatite 310													
1	310-50	0.00	0.00	0.04	0.05	0.00	0.02	0.00	9.98	1.04	0.96	0.00	0.96
	310-51	0.00	0.00	0.03	0.05	0.00	0.01	0.00	10.04	0.95	1.04	0.01	1.05
	310-52	0.00	0.01	0.04	0.06	0.00	0.02	0.00	10.03	1.02	0.97	0.01	0.99
	310-53	0.00	0.00	0.04	0.07	0.01	0.02	0.00	10.00	1.06	0.93	0.01	0.94
3	310-54	0.00	0.00	0.03	0.05	0.00	0.02	0.01	10.03	1.05	0.95	0.00	0.95
	310-55	0.00	0.01	0.03	0.05	0.00	0.02	0.00	10.11	1.12	0.87	0.01	0.88
	Average	0.00	0.00	0.04	0.06	0.00	0.02	0.00	10.03	1.04	0.95	0.01	0.96
A3 Pegmatitic-Carbonatite Grain mount 092													
1	092-56	0.00	0.01	0.07	0.11	0.01	0.03	0.00	10.17	1.02	0.99	0.00	0.99
	092-57	0.00	0.02	0.07	0.11	0.02	0.04	0.00	10.30	0.78	1.22	0.00	1.22
	092-58	0.00	0.00	0.02	0.04	0.00	0.01	0.00	10.17	0.70	1.30	0.00	1.31
	092-59	0.00	0.02	0.04	0.07	0.00	0.02	0.00	10.15	0.79	1.21	0.00	1.21
3	092-60	0.00	0.01	0.02	0.04	0.01	0.02	0.01	10.15	0.83	1.15	0.02	1.17
	092-61	0.00	0.00	0.04	0.08	0.00	0.03	0.00	10.13	0.75	1.24	0.01	1.25
	092-62	0.00	0.00	0.05	0.08	0.00	0.02	0.00	9.99	0.84	1.15	0.01	1.16
	092-63	0.00	0.01	0.03	0.06	0.01	0.02	0.00	10.20	0.78	1.22	0.01	1.22
4	092-64	0.00	0.01	0.04	0.07	0.01	0.02	0.00	10.20	0.52	1.47	0.01	1.48
	092-65	0.00	0.01	0.02	0.05	0.00	0.01	0.00	10.13	0.92	1.08	0.01	1.08
	Average	0.00	0.01	0.04	0.07	0.00	0.02	0.00	10.16	0.79	1.20	0.01	1.21

Table C.4: Composition in of apatite grains by electron microprobe analyses for different rock types from the Oka carbonatite complex (in wt%). A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P2O5	SiO2	As2O5	SO3	CaO	Na2O	FeO	MnO	SrO
A3 Coarse-grained-carbonatite Grain mount 319										
1	319-74	38.48	0.60	0.00	0.13	51.57	0.16	0.00	0.06	0.77
	319-75	38.83	0.74	0.01	0.10	52.30	0.10	0.01	0.03	0.75
2	319-76	40.54	0.43	0.01	0.03	52.25	0.16	0.00	0.02	0.86
	319-77	40.34	0.49	0.00	0.11	52.23	0.25	0.00	0.03	0.84
	319-78	40.54	0.36	0.00	0.00	52.01	0.28	0.04	0.06	0.83
3	319-79	39.62	0.75	0.00	0.12	51.25	0.22	0.01	0.09	0.78
	319-80	39.39	0.56	0.05	0.02	51.65	0.33	0.01	0.03	0.78
	319-81	40.04	0.50	0.04	0.05	51.49	0.15	0.01	0.02	0.87
	Average	39.72	0.55	0.01	0.07	51.94	0.21	0.01	0.04	0.81
A1 Apatite-Okaite 136										
1	136-009	32.08	4.59	0.04	0.20	47.51	0.07	0.00	0.06	0.93
	136-010	33.68	3.91	0.01	0.28	50.45	0.19	0.06	0.07	0.98
	136-011	34.87	3.73	0.00	0.12	50.54	0.20	0.00	0.10	0.94
A1	136-013	31.07	5.55	0.02	0.12	46.43	0.07	0.00	0.01	0.95
	136-014	32.93	4.73	0.00	0.20	47.93	0.09	0.00	0.08	0.88
A2	136-015	30.11	5.62	0.00	0.23	45.98	0.06	0.00	0.04	0.91
	136-016	31.65	4.92	0.02	0.22	47.88	0.07	0.00	0.03	0.91
A3	136-017	33.03	4.35	0.00	0.25	50.79	0.06	0.02	0.04	1.04
	136-018	32.09	5.20	0.02	0.19	47.62	0.05	0.00	0.08	0.96
A4	136-022	32.74	4.99	0.00	0.26	48.47	0.06	0.00	0.04	1.00
	136-023	30.82	5.70	0.01	0.23	46.88	0.08	0.00	0.12	1.02
	Average	31.81	5.13	0.01	0.21	47.75	0.07	0.00	0.06	0.96
2	136-012	33.84	3.79	0.00	0.29	51.19	0.17	0.03	0.04	0.93
	136-019	34.12	3.81	0.00	0.19	50.88	0.10	0.00	0.01	0.99
3	136-020	34.84	3.58	0.00	0.11	48.56	0.14	0.00	0.09	1.04
	136-021	34.38	3.73	0.00	0.27	52.38	0.15	0.00	0.14	1.00
4	136-024	34.48	3.93	0.00	0.19	51.63	0.15	0.01	0.06	0.99
	136-025	34.51	3.85	0.00	0.12	51.62	0.11	0.07	0.06	1.04
	Average	34.09	3.88	0.01	0.20	50.53	0.14	0.02	0.07	0.98

Table C.4: Composition (continued):

GRAIN	SAMPLE	BaO	Y2O3	La2O3	Ce2O3	Pr2O3	Nd2O3	Sm2O3	F	Cl	TOTAL	TOT-O
A3 Coarse-grained-carbonatite Grain mount 319												
1	319-74	0.00	0.03	0.46	0.88	0.07	0.32	0.13	1.40	0.00	95.06	94.47
	319-75	0.01	0.01	0.46	0.85	0.00	0.29	0.27	1.53	0.05	96.34	95.68
2	319-76	0.00	0.00	0.41	0.82	0.08	0.20	0.13	1.99	0.03	97.96	97.12
	319-77	0.00	0.00	0.34	0.83	0.01	0.29	0.06	1.71	0.01	97.54	96.82
	319-78	0.00	0.04	0.33	0.65	0.08	0.23	0.00	1.41	0.00	96.86	96.27
3	319-79	0.02	0.09	0.51	1.02	0.00	0.27	0.04	1.68	0.02	96.49	95.78
	319-80	0.00	0.09	0.46	0.92	0.11	0.27	0.02	1.74	0.01	96.44	95.71
	319-81	0.00	0.09	0.45	0.88	0.06	0.21	0.00	1.91	0.01	96.69	95.88
	Average	0.00	0.03	0.43	0.86	0.05	0.26	0.08	1.67	0.02	96.67	95.97
A1 Apatite-Olakte 136												
1	136-009	0.00	0.04	3.31	5.18	0.37	1.28	0.09	1.03	0.04	96.82	96.38
	136-010	0.04	0.00	1.64	3.11	0.22	0.77	0.28	1.08	0.00	96.77	96.32
	136-011	0.01	0.11	1.66	2.91	0.10	0.87	0.14	1.32	0.01	97.63	97.07
A1	136-013	0.00	0.19	4.00	6.30	0.26	1.44	0.09	1.09	0.01	97.60	97.14
	136-014	0.02	0.15	3.23	5.26	0.19	1.18	0.13	1.06	0.05	98.11	97.65
A2	136-015	0.00	0.06	4.15	6.62	0.35	1.43	0.09	1.07	0.00	96.72	96.27
	136-016	0.00	0.13	3.46	5.66	0.29	1.18	0.16	1.17	0.01	97.76	97.27
A3	136-017	0.07	0.04	2.87	4.44	0.26	1.00	0.00	0.88	0.01	99.15	98.78
	136-018	0.00	0.15	4.02	6.08	0.23	1.27	0.22	0.99	0.03	99.20	98.78
A4	136-022	0.03	0.09	3.65	5.80	0.24	1.38	0.06	1.03	0.03	99.87	99.43
	136-023	0.01	0.19	4.33	7.21	0.43	1.53	0.05	0.97	0.00	99.58	99.17
	Average	0.02	0.13	3.71	5.92	0.28	1.30	0.10	1.03	0.02	98.50	98.06
2	136-012	0.03	0.04	1.59	2.87	0.10	0.83	0.11	1.05	0.03	96.93	96.48
	136-019	0.00	0.04	1.99	3.49	0.15	1.07	0.16	0.94	0.05	97.99	97.58
3	136-020	0.01	0.10	2.02	3.45	0.14	0.81	0.02	1.14	0.03	96.08	95.59
	136-021	0.00	0.16	1.82	3.06	0.18	0.83	0.31	1.09	0.01	99.51	99.05
4	136-024	0.01	0.05	1.72	3.10	0.27	0.93	0.12	1.05	0.03	98.72	98.27
	136-025	0.04	0.13	2.12	3.66	0.15	0.98	0.19	1.13	0.01	99.79	99.31
	Average	0.02	0.07	1.99	3.43	0.19	0.93	0.16	1.09	0.02	97.80	97.34

Table C.4: Atoms per formula unit. Formulae based a charge of 50. A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P	SI	AS	S	SUBT	CA	NA	FE	MN	SR
A3 Coarse-grained-carbonatite Grain mount 319											
1	319-74	5.82	0.11	0.00	0.02	5.95	9.88	0.06	0.00	0.01	0.08
	319-75	5.81	0.13	0.00	0.01	5.95	9.90	0.04	0.00	0.01	0.08
2	319-76	5.95	0.08	0.00	0.00	6.03	9.70	0.05	0.00	0.00	0.09
	319-77	5.92	0.09	0.00	0.01	6.02	9.71	0.08	0.00	0.01	0.09
3	319-78	5.97	0.06	0.00	0.00	6.03	9.69	0.09	0.01	0.01	0.08
	319-79	5.89	0.13	0.00	0.02	6.04	9.64	0.08	0.00	0.01	0.08
3	319-80	5.88	0.10	0.00	0.00	5.98	9.76	0.11	0.00	0.01	0.08
	319-81	5.94	0.09	0.00	0.01	6.04	9.67	0.05	0.00	0.00	0.09
Average											
A1 Apatite-Okalte 136		5.90	0.10	0.00	0.01	6.00	9.74	0.07	0.00	0.01	0.08
1	136-009	5.04	0.85	0.00	0.03	5.92	9.44	0.02	0.00	0.01	0.10
	136-010	5.17	0.71	0.00	0.04	5.91	9.80	0.07	0.01	0.01	0.10
A1	136-011	5.28	0.67	0.00	0.02	5.97	9.69	0.07	0.00	0.02	0.10
	136-013	4.90	1.03	0.00	0.02	5.95	9.26	0.03	0.00	0.00	0.10
A2	136-014	5.08	0.86	0.00	0.03	5.97	9.36	0.03	0.00	0.01	0.09
	136-015	4.82	1.06	0.00	0.03	5.91	9.31	0.02	0.00	0.01	0.10
A3	136-016	4.95	0.91	0.00	0.03	5.89	9.48	0.03	0.00	0.00	0.10
	136-017	5.03	0.78	0.00	0.03	5.84	9.78	0.02	0.00	0.01	0.11
A4	136-018	4.96	0.95	0.00	0.03	5.93	9.31	0.02	0.00	0.01	0.10
	136-022	5.00	0.90	0.00	0.04	5.93	9.36	0.02	0.00	0.01	0.11
Average	136-023	4.81	1.05	0.00	0.03	5.89	9.25	0.03	0.00	0.02	0.11
	Average	4.94	0.94	0.00	0.03	5.91	9.39	0.02	0.00	0.01	0.10
2	136-012	5.17	0.69	0.00	0.04	5.89	9.90	0.06	0.01	0.01	0.10
	136-019	5.19	0.68	0.00	0.03	5.89	9.79	0.04	0.00	0.00	0.10
3	136-020	5.36	0.65	0.00	0.02	6.02	9.45	0.05	0.00	0.01	0.11
	136-021	5.15	0.66	0.00	0.04	5.84	9.93	0.05	0.00	0.02	0.10
4	136-024	5.18	0.70	0.00	0.03	5.91	9.83	0.05	0.00	0.01	0.10
	136-025	5.18	0.68	0.00	0.02	5.87	9.80	0.04	0.01	0.01	0.11
Average											
		5.19	0.70	0.00	0.03	5.92	9.74	0.05	0.00	0.01	0.10

Table C.4 Atoms (continued):

GRAIN	SAMPLE	BA	Y	LA	CE	PR	ND	SM	SUBT	OH	F	CL	SUBT
A3 Coarse-grained-carbonatite Grain mount 319													
1	319-74	0.00	0.00	0.03	0.06	0.01	0.02	0.01	10.14	1.21	0.79	0.00	0.79
	319-75	0.00	0.00	0.03	0.06	0.00	0.02	0.02	10.14	1.13	0.86	0.01	0.87
2	319-76	0.00	0.00	0.03	0.05	0.01	0.01	0.01	9.95	0.90	1.09	0.01	1.10
	319-77	0.00	0.00	0.02	0.05	0.00	0.02	0.00	9.98	1.06	0.94	0.00	0.94
	319-78	0.00	0.00	0.02	0.04	0.01	0.01	0.00	9.96	1.22	0.78	0.00	0.78
3	319-79	0.00	0.01	0.03	0.07	0.00	0.02	0.00	9.94	1.06	0.93	0.01	0.94
	319-80	0.00	0.01	0.03	0.06	0.01	0.02	0.00	10.08	1.03	0.97	0.00	0.97
	319-81	0.00	0.00	0.03	0.06	0.00	0.01	0.00	9.92	0.94	1.06	0.00	1.06
	Average	0.00	0.00	0.03	0.05	0.00	0.02	0.01	10.01	1.07	0.93	0.00	0.93
A1 Apatite-Oxide 136													
1	136-009	0.00	0.00	0.23	0.35	0.03	0.09	0.01	10.27	1.38	0.60	0.01	0.62
	136-010	0.00	0.00	0.11	0.21	0.02	0.05	0.02	10.38	1.38	0.62	0.00	0.62
	136-011	0.00	0.01	0.11	0.19	0.01	0.06	0.01	10.26	1.25	0.75	0.00	0.75
A1	136-013	0.00	0.02	0.28	0.43	0.02	0.10	0.01	10.23	1.36	0.64	0.00	0.64
	136-014	0.00	0.01	0.22	0.35	0.01	0.08	0.01	10.18	1.38	0.61	0.02	0.62
A2	136-015	0.00	0.01	0.29	0.46	0.02	0.10	0.01	10.31	1.36	0.64	0.00	0.64
	136-016	0.00	0.01	0.24	0.38	0.02	0.08	0.01	10.35	1.31	0.69	0.00	0.69
A3	136-017	0.01	0.00	0.19	0.29	0.02	0.06	0.00	10.49	1.49	0.50	0.00	0.51
	136-018	0.00	0.01	0.27	0.41	0.02	0.08	0.01	10.24	1.42	0.57	0.01	0.58
A4	136-022	0.00	0.01	0.24	0.38	0.02	0.09	0.00	10.24	1.41	0.59	0.01	0.60
	136-023	0.00	0.02	0.29	0.49	0.03	0.10	0.00	10.34	1.43	0.57	0.00	0.57
	Average	0.00	0.01	0.25	0.40	0.02	0.09	0.01	10.30	1.40	0.60	0.01	0.60
2	136-012	0.00	0.00	0.11	0.19	0.01	0.05	0.01	10.44	1.39	0.60	0.01	0.61
	136-019	0.00	0.00	0.13	0.23	0.01	0.07	0.01	10.38	1.45	0.53	0.02	0.55
3	136-020	0.00	0.01	0.14	0.23	0.01	0.05	0.00	10.06	1.34	0.66	0.01	0.66
	136-021	0.00	0.02	0.12	0.20	0.01	0.05	0.02	10.52	1.39	0.61	0.00	0.61
4	136-024	0.00	0.01	0.11	0.20	0.02	0.06	0.01	10.39	1.40	0.59	0.01	0.60
	136-025	0.00	0.01	0.14	0.24	0.01	0.06	0.01	10.44	1.37	0.63	0.00	0.63
	Average	0.00	0.01	0.13	0.23	0.01	0.06	0.01	10.35	1.37	0.62	0.01	0.63

Table C.4: Composition in of apatite grains by electron microprobe analyses for different rock types from the Oka carbonatite complex (in wt%). A1= Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P2O5	SiO2	As2O5	SO3	CaO	Na2O	FeO	MnO	SrO
A1 Apatite-Okaite 138 Thin Section										
1	138A-035	32.36	3.90	0.02	0.20	48.42	0.15	0.00	0.12	0.93
	138A-036	32.84	4.14	0.05	0.22	47.71	0.14	0.00	0.03	0.89
2	138A-037	33.42	3.69	0.00	0.15	48.14	0.06	0.01	0.08	0.86
	138A-038	32.92	3.80	0.00	0.17	48.73	0.10	0.01	0.12	0.82
	138A-039	32.10	3.90	0.00	0.22	49.54	0.13	0.08	0.13	0.91
	138A-040	33.42	3.58	0.00	0.15	49.02	0.08	0.06	0.07	0.89
3	138A-041	33.20	3.69	0.00	0.06	49.55	0.10	0.00	0.10	0.97
	138A-042	32.92	4.01	0.00	0.21	49.15	0.14	0.02	0.14	0.91
4	138A-044	33.14	3.63	0.00	0.19	49.94	0.13	0.01	0.14	0.91
	138A-043	33.94	3.56	0.03	0.16	49.28	0.08	0.00	0.15	0.88
	138A-045	34.07	3.57	0.03	0.17	50.76	0.12	0.00	0.05	0.93
5	138A-046	33.67	3.70	0.00	0.12	50.75	0.11	0.00	0.09	0.89
	138A-047	32.17	4.20	0.03	0.13	49.72	0.14	0.06	0.08	0.84
Average		33.09	3.80	0.01	0.17	49.29	0.11	0.02	0.10	0.89
A1 Apatite-Okaite Grain mount 138										
1	138-82	34.05	3.77	0.02	0.25	49.41	0.14	0.00	0.09	1.11
	138-83	32.60	4.15	0.00	0.17	48.93	0.16	0.00	0.02	1.04
	138-84	32.98	4.13	0.01	0.24	48.76	0.12	0.01	0.10	1.02
	138-85	32.33	4.05	0.00	0.19	49.20	0.09	0.00	0.07	0.99
2	138-86	33.08	4.24	0.03	0.17	48.81	0.14	0.02	0.00	1.05
	138-87	31.75	4.34	0.00	0.22	48.84	0.27	0.02	0.12	1.02
	138-88	32.37	4.21	0.03	0.26	48.84	0.24	0.01	0.09	1.12
Average		32.74	4.13	0.01	0.21	48.97	0.17	0.01	0.07	1.05
A3 Nepheline-Okaite 106 & 110										
1	106-026	35.50	2.84	0.00	0.33	51.30	0.04	0.09	0.09	1.09
	106-027	36.28	2.69	0.00	0.56	53.65	0.02	0.06	0.00	1.19
2	106-028	36.20	2.71	0.04	0.22	52.03	0.05	0.03	0.05	1.16
	106-029	38.63	1.41	0.00	0.36	53.43	0.01	0.04	0.02	1.01
	106-030	37.96	1.55	0.00	0.20	52.43	0.00	0.06	0.00	2.02
3	110-031	34.11	3.28	0.00	0.27	51.52	0.05	0.03	0.00	0.85
	110-032	38.15	1.72	0.00	0.54	54.16	0.01	0.07	0.03	0.83
4	110-033	34.93	3.10	0.03	0.37	51.88	0.05	0.01	0.09	0.79
	110-034	39.48	1.38	0.06	0.37	53.91	0.00	0.02	0.03	1.02
Average		36.80	2.30	0.01	0.36	52.70	0.03	0.05	0.03	1.11

Table C.4: Composition (continued):

GRAIN	SAMPLE	BaO	Y2O3	La2O3	Ce2O3	Pr2O3	Nd2O3	Sm2O3	F	Cl	TOTAL	TOT-O
A1 Apatite-Okaite 138 Thin Section												
1	138A-035	0.02	0.07	1.58	2.73	0.01	0.83	0.07	1.31	0.01	92.73	92.18
	138A-036	0.06	0.09	1.89	3.13	0.13	0.93	0.00	1.40	0.03	93.68	93.08
2	138A-037	0.08	0.07	1.81	3.42	0.07	0.96	0.03	1.46	0.04	94.35	93.73
	138A-038	0.03	0.06	1.60	2.95	0.17	0.65	0.14	1.37	0.01	93.65	93.07
	138A-039	0.00	0.08	1.61	3.00	0.22	0.79	0.03	1.29	0.09	94.12	93.56
	138A-040	0.00	0.05	1.92	3.35	0.10	0.89	0.00	1.53	0.02	95.13	94.48
3	138A-041	0.00	0.10	2.05	3.54	0.09	1.08	0.02	1.57	0.03	96.15	95.48
	138A-042	0.03	0.07	1.72	3.11	0.10	0.86	0.01	1.35	0.00	94.75	94.18
4	138A-044	0.03	0.03	1.59	2.88	0.07	0.71	0.06	1.45	0.04	94.95	94.33
	138A-043	0.00	0.08	1.97	3.52	0.11	0.87	0.17	1.53	0.05	96.38	95.72
	138A-045	0.04	0.02	1.49	2.58	0.03	0.76	0.06	1.40	0.03	96.11	95.51
5	138A-046	0.03	0.08	1.62	2.86	0.03	0.81	0.01	1.43	0.03	96.23	95.62
	138A-047	0.06	0.02	1.81	3.25	0.13	0.86	0.00	1.33	0.02	94.85	94.29
	Average	0.03	0.06	1.74	3.10	0.10	0.85	0.05	1.42	0.03	94.85	94.25
A1 Apatite-Okaite Grain mount 138												
1	138-82	0.02	0.08	1.79	2.98	0.17	0.91	0.00	1.35	0.01	96.15	95.58
	138-83	0.00	0.09	1.91	3.26	0.17	0.86	0.11	1.47	0.02	94.96	94.34
	138-84	0.04	0.03	1.84	3.35	0.21	0.96	0.27	1.54	0.00	95.61	94.96
	138-85	0.06	0.12	1.83	3.09	0.23	0.76	0.05	1.40	0.01	94.47	93.88
2	138-86	0.02	0.09	1.82	3.20	0.14	0.81	0.06	1.74	0.00	95.42	94.69
	138-87	0.01	0.02	1.84	3.25	0.28	0.91	0.14	1.37	0.04	94.44	93.85
	138-88	0.00	0.12	1.90	3.28	0.27	0.88	0.19	1.06	0.03	94.90	94.45
	Average	0.02	0.08	1.85	3.20	0.21	0.87	0.12	1.42	0.02	95.14	94.54
A3 Nepheline-Okaite 106 & 110												
1	106-026	0.05	0.05	1.00	1.74	0.10	0.33	0.10	1.83	0.01	96.49	95.72
	106-027	0.06	0.04	0.44	0.63	0.00	0.21	0.11	1.65	0.01	97.60	96.90
2	106-028	0.00	0.03	0.87	1.47	0.00	0.52	0.02	1.96	0.01	97.37	96.54
	106-029	0.00	0.01	0.34	0.29	0.00	0.08	0.00	2.10	0.00	97.73	96.85
	106-030	0.00	0.02	0.51	0.66	0.00	0.17	0.14	1.99	0.02	97.73	96.89
3	110-031	0.07	0.02	1.39	2.13	0.00	0.50	0.02	2.21	0.01	96.46	95.53
	110-032	0.11	0.05	0.31	0.45	0.05	0.15	0.04	2.16	0.00	98.83	97.92
4	110-033	0.00	0.09	0.98	1.76	0.02	0.50	0.05	2.22	0.01	96.88	95.94
	110-034	0.06	0.04	0.29	0.45	0.00	0.07	0.01	2.44	0.00	99.63	98.60
	Average	0.04	0.04	0.68	1.06	0.02	0.28	0.05	2.06	0.01	97.64	96.77

Table C.4: Atoms per formula unit. Formulae based a charge of 50. A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P	SI	AS	S	SUBT	CA	NA	FE	MIN	SR
A1 Apatite-Okaite 138 Thin Section											
1	138A-035	5.18	0.74	0.00	0.03	5.94	9.80	0.05	0.00	0.02	0.10
	138A-036	5.20	0.78	0.01	0.03	6.01	9.57	0.05	0.00	0.01	0.10
	138A-037	5.27	0.69	0.00	0.02	5.98	9.61	0.02	0.00	0.01	0.09
2	138A-038	5.22	0.71	0.00	0.02	5.95	9.77	0.04	0.00	0.02	0.09
	138A-039	5.10	0.73	0.00	0.03	5.86	9.95	0.05	0.01	0.02	0.10
	138A-040	5.24	0.66	0.00	0.02	5.93	9.73	0.03	0.01	0.01	0.10
3	138A-041	5.19	0.68	0.00	0.01	5.88	9.80	0.04	0.00	0.02	0.10
	138A-042	5.17	0.74	0.00	0.03	5.94	9.76	0.05	0.00	0.02	0.10
	138A-044	5.19	0.67	0.00	0.03	5.89	9.90	0.05	0.00	0.02	0.10
4	138A-043	5.26	0.65	0.00	0.02	5.94	9.67	0.03	0.00	0.02	0.09
	138A-045	5.24	0.65	0.00	0.02	5.92	9.89	0.04	0.00	0.01	0.10
	138A-046	5.20	0.68	0.00	0.02	5.89	9.92	0.04	0.00	0.01	0.10
5	138A-047	5.07	0.78	0.00	0.02	5.88	9.92	0.05	0.01	0.01	0.09
	Average	5.19	0.70	0.00	0.02	5.92	9.79	0.04	0.00	0.02	0.10
A1 Apatite-Okaite Grain mount 138											
1	138-82	5.25	0.69	0.00	0.03	5.97	9.64	0.05	0.00	0.01	0.12
	138-83	5.13	0.77	0.00	0.02	5.93	9.75	0.06	0.00	0.00	0.11
	138-84	5.16	0.76	0.00	0.03	5.96	9.65	0.04	0.00	0.02	0.11
	138-85	5.11	0.76	0.00	0.03	5.90	9.85	0.03	0.00	0.01	0.11
2	138-86	5.17	0.78	0.00	0.02	5.98	9.66	0.05	0.00	0.00	0.11
	138-87	5.05	0.81	0.00	0.03	5.89	9.82	0.10	0.00	0.02	0.11
	138-88	5.09	0.78	0.00	0.04	5.92	9.73	0.09	0.00	0.01	0.12
	Average	5.14	0.77	0.00	0.03	5.93	9.73	0.06	0.00	0.01	0.11
A3 Nepheline-Okaite 106 & 110											
1	106-026	5.40	0.51	0.00	0.04	5.95	9.87	0.02	0.01	0.01	0.11
	106-027	5.39	0.47	0.00	0.07	5.93	10.08	0.01	0.01	0.00	0.12
	106-028	5.44	0.48	0.00	0.03	5.96	9.91	0.02	0.00	0.01	0.12
2	106-029	5.69	0.25	0.00	0.05	5.98	9.96	0.00	0.01	0.00	0.10
	106-030	5.65	0.27	0.00	0.03	5.95	9.88	0.00	0.01	0.00	0.21
	110-031	5.25	0.60	0.00	0.04	5.89	10.04	0.02	0.01	0.00	0.09
3	110-032	5.58	0.30	0.00	0.07	5.95	10.03	0.01	0.01	0.01	0.08
	110-033	5.32	0.56	0.00	0.05	5.93	9.99	0.02	0.00	0.01	0.08
	110-034	5.72	0.24	0.01	0.05	6.01	9.88	0.00	0.00	0.00	0.10
	Average	5.49	0.41	0.00	0.05	5.95	9.96	0.01	0.01	0.01	0.11

Table C.4 Atoms (continued):

GRAIN	SAMPLE	BA	Y	LA	CE	PR	ND	SM	SUBT	OH	F	CL	SUBT
A1 Apatite-Okaite 138 Thin Section													
1	138A-035	0.00	0.01	0.11	0.19	0.00	0.06	0.00	10.34	1.21	0.79	0.00	0.79
	138A-036	0.00	0.01	0.13	0.22	0.01	0.06	0.00	10.15	1.16	0.83	0.01	0.84
2	138A-037	0.01	0.01	0.12	0.23	0.01	0.06	0.00	10.18	1.13	0.86	0.01	0.87
	138A-038	0.00	0.01	0.11	0.20	0.01	0.04	0.01	10.30	1.19	0.81	0.00	0.82
	138A-039	0.00	0.01	0.11	0.21	0.02	0.05	0.00	10.53	1.21	0.76	0.03	0.79
	138A-040	0.00	0.01	0.13	0.23	0.01	0.06	0.00	10.31	1.10	0.90	0.01	0.90
3	138A-041	0.00	0.01	0.14	0.24	0.01	0.07	0.00	10.42	1.07	0.92	0.01	0.93
	138A-042	0.00	0.01	0.12	0.21	0.01	0.06	0.00	10.33	1.21	0.79	0.00	0.79
4	138A-044	0.00	0.00	0.11	0.20	0.01	0.05	0.00	10.44	1.14	0.85	0.01	0.86
	138A-043	0.00	0.01	0.13	0.24	0.01	0.06	0.01	10.27	1.10	0.89	0.01	0.90
	138A-045	0.00	0.00	0.10	0.17	0.00	0.05	0.00	10.37	1.19	0.80	0.01	0.81
5	138A-046	0.00	0.01	0.11	0.19	0.00	0.05	0.00	10.44	1.17	0.82	0.01	0.83
	138A-047	0.00	0.00	0.13	0.22	0.01	0.06	0.00	10.51	1.21	0.79	0.01	0.79
Average													
		0.00	0.01	0.12	0.21	0.01	0.06	0.00	10.35	1.16	0.83	0.01	0.84
A1 Apatite-Okaite Grain mount 138													
1	138-82	0.00	0.01	0.12	0.20	0.01	0.06	0.00	10.22	1.22	0.78	0.01	0.78
	138-83	0.00	0.01	0.13	0.22	0.01	0.06	0.01	10.36	1.13	0.86	0.01	0.87
	138-84	0.00	0.00	0.13	0.23	0.01	0.06	0.02	10.27	1.10	0.90	0.00	0.90
	138-85	0.00	0.01	0.13	0.21	0.02	0.05	0.00	10.43	1.17	0.83	0.00	0.83
2	138-86	0.00	0.01	0.12	0.22	0.01	0.05	0.00	10.24	0.98	1.02	0.00	1.02
	138-87	0.00	0.00	0.13	0.22	0.02	0.06	0.01	10.49	1.17	0.82	0.01	0.83
	138-88	0.00	0.01	0.13	0.22	0.02	0.06	0.01	10.40	1.37	0.62	0.01	0.63
Average													
		0.00	0.01	0.13	0.22	0.01	0.06	0.01	10.35	1.16	0.83	0.00	0.84
A3 Nepheline-Okaite 106 & 110													
1	106-026	0.00	0.00	0.07	0.12	0.01	0.02	0.01	10.25	0.96	1.04	0.00	1.05
	106-027	0.00	0.00	0.03	0.04	0.00	0.01	0.01	10.32	1.08	0.92	0.00	0.92
2	106-028	0.00	0.00	0.06	0.10	0.00	0.03	0.00	10.24	0.90	1.10	0.00	1.11
	106-029	0.00	0.00	0.02	0.02	0.00	0.01	0.00	10.12	0.84	1.16	0.00	1.16
	106-030	0.00	0.00	0.03	0.04	0.00	0.01	0.01	10.19	0.89	1.11	0.01	1.11
3	110-031	0.01	0.00	0.09	0.14	0.00	0.03	0.00	10.43	0.72	1.27	0.01	1.28
	110-032	0.01	0.01	0.02	0.03	0.00	0.01	0.00	10.21	0.82	1.18	0.00	1.18
4	110-033	0.00	0.01	0.07	0.12	0.00	0.03	0.00	10.34	0.73	1.26	0.01	1.27
	110-034	0.00	0.00	0.02	0.03	0.00	0.00	0.00	10.05	0.68	1.32	0.00	1.32
Average													
		0.00	0.00	0.04	0.07	0.00	0.02	0.00	10.24	0.85	1.15	0.00	1.15

Table C.4: Composition in of apatite grains by electron microprobe analyses for different rock types from the Oka carbonatite complex (in wt%). A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P2O5	SiO2	As2O5	SO3	CaO	Na2O	FeO	MnO	SrO
A3 Calcite-Ijolite 120										
1	120-25	41.19	0.33	0.00	0.04	52.36	0.34	0.02	0.00	0.56
	120-26	40.59	0.30	0.00	0.03	53.01	0.29	0.02	0.03	0.51
2	120-27	41.01	0.48	0.02	0.09	52.72	0.25	0.06	0.07	0.59
	120-28	41.04	0.40	0.02	0.09	52.92	0.26	0.01	0.00	0.51
3	120-29	41.03	0.19	0.02	0.06	54.29	0.15	0.00	0.02	0.59
	120-30	40.09	0.88	0.00	0.03	52.85	0.14	0.02	0.01	0.73
	120-31	41.08	0.28	0.04	0.05	53.33	0.33	0.03	0.02	0.74
	Average	40.86	0.41	0.01	0.06	53.07	0.25	0.02	0.02	0.60
4	120-32	36.36	3.02	0.02	0.13	50.02	0.07	0.05	0.07	0.66
	120-33	37.03	2.12	0.00	0.10	51.49	0.11	0.00	0.00	0.62
	120-34	36.48	2.80	0.01	0.09	50.17	0.10	0.09	0.02	0.71
	Average	36.62	2.65	0.01	0.11	50.56	0.09	0.05	0.03	0.66
A4 Melanite-Ijolite 089										
1	089-15	39.44	1.38	0.04	0.13	54.12	0.10	0.03	0.00	0.60
	089-16	36.70	2.61	0.00	0.25	51.80	0.13	0.00	0.09	0.60
2	089-17	38.34	2.05	0.00	0.15	52.13	0.11	0.05	0.03	0.70
	089-18	36.50	2.58	0.00	0.25	51.33	0.15	0.10	0.00	0.67
3	089-19	37.23	2.15	0.00	0.14	51.21	0.05	0.00	0.07	0.56
	089-20	36.78	2.25	0.00	0.18	52.16	0.10	0.02	0.04	0.60
4	089-21	36.85	2.30	0.00	0.14	52.02	0.14	0.04	0.03	0.61
	089-22	36.60	2.50	0.00	0.19	51.54	0.16	0.00	0.00	0.65
5	089-23	36.08	2.51	0.00	0.29	52.39	0.19	0.08	0.01	0.58
	089-24	37.65	2.25	0.04	0.24	52.49	0.12	0.00	0.00	0.58
	Average	37.22	2.26	0.01	0.20	52.12	0.13	0.03	0.03	0.62

Table C.4: Composition (continued):

GRAIN	SAMPLE	BaO	Y2O3	La2O3	Ce2O3	Pr2O3	Nd2O3	Sm2O3	F	Cl	TOTAL	TOT-O
A3 Calcite-Ijolite 120												
1	120-25	0.02	0.02	0.60	1.16	0.00	0.39	0.00	1.66	0.01	98.70	98.00
	120-26	0.05	0.05	0.56	1.01	0.00	0.29	0.03	1.60	0.00	98.37	97.70
2	120-27	0.04	0.05	0.62	1.12	0.18	0.43	0.01	1.62	0.04	99.40	98.71
	120-28	0.02	0.09	0.53	0.99	0.00	0.34	0.21	1.54	0.00	98.97	98.32
3	120-29	0.05	0.02	0.23	0.57	0.00	0.11	0.00	1.82	0.01	99.16	98.39
	120-30	0.00	0.08	0.78	1.32	0.13	0.45	0.08	1.78	0.03	99.40	98.64
	120-31	0.03	0.01	0.47	1.02	0.09	0.25	0.06	1.77	0.00	99.60	98.85
	Average	0.03	0.05	0.54	1.03	0.06	0.32	0.06	1.68	0.01	99.09	98.37
4	120-32	0.04	0.16	1.99	3.94	0.26	1.20	0.23	1.83	0.00	100.05	99.28
	120-33	0.03	0.19	1.43	2.92	0.29	0.87	0.25	1.63	0.01	99.09	98.40
	120-34	0.08	0.03	1.49	3.56	0.30	1.28	0.14	1.67	0.02	99.04	98.33
	Average	0.05	0.13	1.64	3.47	0.28	1.12	0.21	1.71	0.01	99.39	98.67
A4 Melanite-Ijolite 089												
1	089-15	0.04	0.00	0.58	1.15	0.14	0.55	0.17	1.58	0.00	100.05	99.38
	089-16	0.02	0.08	0.86	1.79	0.00	0.48	0.12	1.73	0.03	97.29	96.55
2	089-17	0.01	0.01	0.75	1.44	0.05	0.51	0.16	1.56	0.03	98.08	97.42
	089-18	0.05	0.08	1.11	2.15	0.16	0.69	0.02	1.45	0.00	97.29	96.68
3	089-19	0.00	0.01	1.05	2.09	0.00	0.82	0.00	1.68	0.02	97.08	96.37
	089-20	0.00	0.04	0.71	1.45	0.08	0.38	0.16	1.58	0.01	96.54	95.87
4	089-21	0.01	0.03	0.81	1.68	0.06	0.52	0.05	1.66	0.03	96.98	96.27
	089-22	0.00	0.03	0.89	1.83	0.14	0.51	0.00	1.58	0.02	96.64	95.97
5	089-23	0.00	0.07	0.82	1.72	0.14	0.63	0.00	1.75	0.00	97.26	96.52
	089-24	0.01	0.07	0.65	1.48	0.17	0.52	0.07	1.68	0.01	98.03	97.32
	Average	0.01	0.04	0.82	1.68	0.09	0.56	0.08	1.63	0.02	97.52	96.84

Table C.4: Atoms per formula unit. Formulae based a charge of 50. A1=Husereau Hills, A2=Bond Zone, A3=St. Lawrence Mines, A4=Nature Centre.

GRAIN	SAMPLE	P	SI	AS	S	SUBT	CA	NA	FE	MN	SR
A3 Calcite-Ijolite 120											
1	120-25	5.98	0.06	0.00	0.01	6.04	9.61	0.11	0.00	0.00	0.06
	120-26	5.92	0.05	0.00	0.00	5.98	9.79	0.10	0.00	0.01	0.05
	120-27	5.92	0.08	0.00	0.01	6.02	9.64	0.08	0.01	0.01	0.06
	120-28	5.94	0.07	0.00	0.01	6.02	9.69	0.09	0.00	0.00	0.05
3	120-29	5.92	0.03	0.00	0.01	5.97	9.92	0.05	0.00	0.00	0.06
	120-30	5.83	0.15	0.00	0.01	5.99	9.73	0.05	0.00	0.00	0.07
	120-31	5.93	0.05	0.00	0.01	5.99	9.74	0.11	0.00	0.00	0.07
	Average	5.92	0.07	0.00	0.01	6.00	9.73	0.08	0.00	0.00	0.06
4	120-32	5.43	0.53	0.00	0.02	5.98	9.45	0.02	0.01	0.01	0.07
	120-33	5.53	0.37	0.00	0.01	5.92	9.73	0.04	0.00	0.00	0.06
	120-34	5.47	0.50	0.00	0.01	5.98	9.52	0.04	0.01	0.00	0.07
	Average	5.48	0.47	0.00	0.01	5.96	9.57	0.03	0.01	0.00	0.07
A4 Melanite-Ijolite 089											
1	089-15	5.70	0.24	0.00	0.02	5.96	9.90	0.03	0.00	0.00	0.06
	089-16	5.50	0.46	0.00	0.03	5.99	9.82	0.04	0.00	0.01	0.06
2	089-17	5.65	0.36	0.00	0.02	6.03	9.72	0.04	0.01	0.01	0.07
	089-18	5.48	0.46	0.00	0.03	5.97	9.75	0.05	0.02	0.00	0.07
3	089-19	5.59	0.38	0.00	0.02	5.99	9.74	0.02	0.00	0.01	0.06
	089-20	5.53	0.40	0.00	0.02	5.96	9.93	0.04	0.00	0.01	0.06
4	089-21	5.53	0.41	0.00	0.02	5.96	9.89	0.05	0.01	0.01	0.06
	089-22	5.51	0.44	0.00	0.03	5.98	9.83	0.06	0.00	0.00	0.07
5	089-23	5.43	0.45	0.00	0.04	5.92	9.98	0.06	0.01	0.00	0.06
	089-24	5.57	0.39	0.00	0.03	6.00	9.82	0.04	0.00	0.00	0.06
	Average	5.55	0.40	0.00	0.03	5.97	9.84	0.04	0.00	0.00	0.06

Table C.4 Atoms (continued):

GRAIN	SAMPLE	BA	Y	LA	CE	PR	ND	SM	SUBT	OH	F	CL	SURT
A3 Calcite-Ijolite 120													
1	120-25	0.00	0.00	0.04	0.07	0.00	0.02	0.00	10.92	1.10	0.90	0.00	0.90
	120-26	0.00	0.00	0.04	0.06	0.00	0.02	0.00	10.07	1.13	0.87	0.00	0.87
2	120-27	0.00	0.00	0.04	0.07	0.01	0.03	0.00	11.95	1.12	0.88	0.01	0.89
	120-28	0.00	0.01	0.03	0.06	0.00	0.02	0.01	9.96	1.17	0.83	0.00	0.83
3	120-29	0.00	0.00	0.01	0.04	0.00	0.01	0.00	13.09	1.01	0.98	0.00	0.99
	120-30	0.00	0.01	0.05	0.08	0.01	0.03	0.01	10.04	1.03	0.97	0.01	0.97
	120-31	0.00	0.00	0.03	0.06	0.01	0.02	0.00	10.05	1.04	0.96	0.00	0.96
	Average	0.00	0.00	0.03	0.06	0.00	0.02	0.00	10.87	1.09	0.91	0.00	0.91
4	120-32	0.00	0.02	0.13	0.25	0.02	0.08	0.01	10.07	0.98	1.02	0.00	1.02
	120-33	0.00	0.02	0.09	0.19	0.02	0.06	0.02	10.22	1.09	0.91	0.00	0.91
	120-34	0.01	0.00	0.10	0.23	0.02	0.08	0.01	10.09	1.06	0.94	0.01	0.94
	Average	0.00	0.01	0.11	0.22	0.02	0.07	0.01	10.13	1.04	0.96	0.00	0.96
A4 Melanite-Ijolite 089													
1	089-15	0.00	0.00	0.04	0.07	0.01	0.03	0.01	11.16	1.15	0.85	0.00	0.85
	089-16	0.00	0.01	0.06	0.12	0.00	0.03	0.01	10.15	1.03	0.97	0.01	0.97
2	089-17	0.00	0.00	0.05	0.09	0.00	0.03	0.01	12.03	1.13	0.86	0.01	0.87
	089-18	0.00	0.01	0.07	0.14	0.01	0.04	0.00	10.17	1.19	0.81	0.00	0.81
3	089-19	0.00	0.00	0.07	0.14	0.00	0.05	0.00	13.08	1.05	0.94	0.01	0.95
	089-20	0.00	0.00	0.05	0.09	0.01	0.02	0.01	10.22	1.11	0.89	0.01	0.90
4	089-21	0.00	0.00	0.05	0.11	0.00	0.03	0.00	14.22	1.06	0.93	0.01	0.94
	089-22	0.00	0.00	0.06	0.12	0.01	0.03	0.00	10.17	1.10	0.89	0.01	0.90
5	089-23	0.00	0.01	0.05	0.11	0.01	0.04	0.00	15.34	1.01	0.99	0.00	0.99
	089-24	0.00	0.01	0.04	0.09	0.01	0.03	0.00	10.12	1.07	0.93	0.00	0.93
	Average	0.00	0.00	0.05	0.11	0.01	0.04	0.00	10.17	1.09	0.91	0.00	0.91