MINERALOGY, GEOCHEMISTRY, AND GEOCHRONOLOGY OF THE YOGO DIKE SAPPHIRE DEPOSIT, MONTANA

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Department of Geological Sciences)

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

March, 1995

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Date April 20 1995

DE-6 (2/88)

ABSTRACT

The Yogo dike is located in the central alkalic province of Montana, on the eastern flank of the Little Belt Mountains, about 95 km southeast of Great Falls. It has been sporadically mined since the end of the last century for its gem quality blue sapphires. The intrusion is classified as an ouachitite of the ultramafic lamprophyre group. It is composed of phlogopite and clinopyroxene megacrysts set into a matrix of phlogopite, clinopyroxene, calcite, analcime, magnetite, and apatite. Accessory minerals include sapphire (gem quality corundum) and pleonaste (Mg-Al-Fe spinel). The rock also contains ocelli composed of calcite, dolomite, ankerite, barite, analcime with or without pyrite, and amphibole.

Geochemical analysis of the Yogo dike revealed that it can not be precisely classified. It shows characteristics similar to ouachitite, damkjernite and aillikite, which all belong to the ultramafic group of lamprophyres. Mineralogically, the rock is more akin to ouachitite. It is ultramafic in character and is similar in many ways to a carbonatite. It is poor in silica and rich in Ca, Mg, Cr, Ba, and Sr. Some of the samples studied are alkaline while some are not. The geochemistry of the Yogo dike was compared to the Yogo Peak intrusion located some 16 km northwest of the dike. Some authors have proposed that the two are genetically related but Pearce element diagrams show that they are not.

Phlogopite and pyroxene crystals are typically zoned. Phlogopite megacrysts often show pyroxene and apatite inclusions. The phlogopite crystals have Mg-rich cores and Fe, Al and Ba-rich rims. The pyroxenes can show complex zoning; cores are typically diopsidic or augitic, and rims are progressively richer in Al (up to 11 wt.% Al₂O₃), Fe, and Ti, and poorer in Mg and Si. Some of the pyroxenes are Cr-rich, with up to 1.65 wt.% Cr₂O₃, and all are poor in Na.

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Magnetite is sometimes zoned with Al-rich rims. Sapphires are Fe-poor. Their blue colouration is due to intervalence charge transfer phenomena between Fe^{2+} and Ti^{4+} . The purple colour of some Yogo sapphires is due to a small amount of Cr-content.

A phlogopite separate from the Yogo dike yielded a K-Ar date of 48.2 ± 1.3 Ma. The depth at which the Yogo magma originated is hard to bracket due to lack of assemblages to which geothermobaromety can be applied. A garnet-clinopyroxene-plagioclase granulite xenolith was found. The garnets are pyrope-rich with subordinate almandine, grossular and andradite components. The pyroxenes are Al-rich and Na-poor. Geothermobarometry applied to this xenolith yielded a pressure estimate of between 12 to 20 kb (~40 to 70 km depth) and temperatures around 850° C.

Based on this study as well as previous studies, the sapphires are thought to be xenocrysts in the dike. Arguments in favor of this statement are: (1) the Yogo magma is not corundum normative, thus preventing the crystallization of Al-rich phases as phenocrysts; (2) crystals are highly resorbed and always rimmed by pleonaste spinel, which indicates a disequilibrium reaction between the magma and the sapphires; (3) two sapphire-bearing xenoliths have been found during previous studies by Dahy (1988, 1991), a sapphirepyroxene-plagioclase xenolith and a pyroxene-phlogopite-sapphire autolith; (4) a few inclusions found in the sapphires indicate a different paragenesis than the dike rock; (5) the Mg-rich pleonaste spinels found as accessory minerals in the rock seem to indicate that Al-rich material was mixed with the Yogo magma. This type of spinel is often found with sapphires and is usually the result of moderate to high temperature metamorphism of Al-rich phases. The Al-rich material was probably sapphire-bearing. Point (3) should be enough to prove the xenocrystic nature of the sapphires, but the sapphires in the xenolith were identified only by eye. All minerals analyzed show a drastic increase in Al content in their outside rims. This suggests contamination of the magma during its ascent by Al-rich, corundum-bearing material. The high temperature of the ultrabasic magma partially resorbed the corundum and reacted with it, forming pleonaste. Al-rich phases (such as phlogopite and Al-rich pyroxene) also reacted with the new magma to produce pleonaste spinel.

The grade of sapphires in the dike ranges between 5 carats (1 ppm) to 100 carats (20 ppm) per ton; few areas are barren. Sapphires range in size from about 0.33 carats to 8 carats.

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ACKNOWLEDGMENTS

I would like to thank Dr. L.A. Groat for suggesting and supervising the project. I would also like to thank Roncor Incorporated (Sapphire International) for allowing access to the site, and for providing housing in Sapphire Village. Joe Iwawaki (manager of the mine) was especially helpful. I would also like to thank Terri Ottaway (of the Royal Ontario Museum) and Lindsay Kelly for help with the field work, and Dr. R. Taylor of Carleton University for the geochemical analyses.

1. INTRODUCTION

1.1 Location

The sapphire-bearing Yogo dike is located on the northeastern flank of the Little Belt Mountains, in the Central Montana alkalic province (Figures 1.1 and 1.2). The dike is approximately 72 km southwest of Lewistown, 95 km southeast of Great Falls, and 24 km south of the small ghost town of Utica. The dike runs parallel to the Judith River and is cut by Yogo Creek to the west. The mine is at an elevation of approximately 1500 m and the nearby mountains reach elevations of 2700 m. Mining is restricted to the summer and early fall due to heavy snow accumulations.

1.2 Sapphire Parageneses

Corundum occurs in a wide variety of geological environments. It can be igneous, hydrothermal or metamorphic in origin. Corundum of igneous origin is found in aluminous silica-poor pegmatites, anorthosite, nepheline syenite, serpentinite, pyroxenite, basic minette, and alkali basalts. The most widespread host rock for gem-quality corundum is alkali basalt. It is uncertain, however, if corundum is a magmatic phase in the magma. Many authors (Keller, 1982; Jobbins and Berrangé, 1981) are of the opinion that the sapphires are xenocrysts. The placer deposits of Thailand, Australian, China, Nigeria, and Cambodia are all derived from alkali basalt. Metamorphic deposits include gneisses derived from Al-rich sediments, granulites, skarns, metamorphosed bauxite, and marble (Hughes, 1990). The famous ruby mines of Burma are derived from an impure marble. Corundum of unique parageneses include the deposits of Yogo Gulch and Loch Road in Scotland (where the sapphires are found in a monchiquite), and the Tanzanian deposits where the host rock is a vermiculite (altered serpentinite).



Figure 1.1: Location of the Yogo dike in Montana (after Voynick, 1985). Placer sapphire deposits to the west of the dike are shown by diamonds on the map.



Figure 1.2: General map of the area around the Yogo dike (after Voynick, 1985).

Gem-quality corundum is recovered almost entirely from secondary or placer deposits. The major exceptions are the Kashmir mines in India (now almost closed), Yogo Gulch, and the sapphire and ruby mines in Tanzania where the stones are obtained from a serpentinite pipe and the vermiculite alteration zone.

1.3 Proposed Study

The broad objectives of the study were as follows:

- 1. To determine whether the sapphires are xenocrysts or phenocrysts.
- 2. To determine the temperature, pressure and depth of formation of the lamprophyric magma.
- 3. To investigate the geochemistry of the host rock and to look at possible petrological relationships between the dike rock and the other igneous rocks in the area.
- 4. To determine the age of the dike.

1.4 Field Work

Field work entailed two weeks at the Yogo Gulch property in July, 1992. Roncor Incorporated gave permission to study all areas of the property, including the Kunisaki tunnel located at the American Mine. Most of the field work involved sampling rather than mapping. Little was added to the map by Dahy (1988) since the exposure was very poor (the geological map is Figure 2.3, inside the back cover). The dike is mined out on surface for almost its entire length, except for the mining area at Kelly Coulee where the rock is highly weathered. Almost a century of mining has left deep trenches (2 to 10 m) in the limestone (Figure 1.3) and there are a few shafts up to approximately 100 m in depth. Access to the bottom of the trenches was limited and in some cases the dike rock was buried under piles of limestone debris detached

from the walls. Furthermore, the "Intergem Cut" (active 1980 to 1985) has been filled in to meet new mining laws. It was possible to collect *in situ* samples only at Kelly Coulee, west of the American Mine.

57 samples were collected from different areas of the Yogo dike: 19 from the Middle Mine, 16 from Kelly Coulee, seven from the English Mine, two from the Intergem Cut, six on the western extension of the dike, two from the 4th of July claim (located between the Middle Mine and the American Mine), two from the barren dike located north of the Yogo dike, two of uncertain locality and one from a minette sill. Fresh samples were collected at the Middle and English Mines from stock piles accumulated during mining conducted in 1992, in the case of the Middle Mine, and before 1930, for the English Mine. The rock was stockpiled because of its low degree of weathering, which made it unsuitable for the washing process used for recovering sapphires from the rock. It is highly probable that the samples from the English Mine are not as fresh as the ones from the Middle Mine, due to sixty years of exposure. Samples collected at the Intergem Cut include only a red breccia facies, since no dike rock was accessible. Many weathered samples were collected from the working area of Kelly Coulee (Figure 1.4). These include yellow and red diatreme (?) and sapphire-bearing limestone breccia samples. The western extension of the dike was also sampled for about 1 km. The samples, from the cliffs north of Kelly Coulee, are yellow in colour and include only limestone and a few probable dike breccias. One sample obtained near the adit was sapphirebearing. Sampling of the Kunisaki tunnel was impossible, since no maintenance work has been done in the tunnel for many years and some areas near the entrance have collapsed.

A few sapphires were found *in situ* in the rocks from the English and Middle mines and Kelly Coulee. Sapphires were also collected from the rejects of the mining operations. These are tabular crystals generally less than 4 mm in diameter. The bulk of the material (about 300 ct) is blue and violet blue, but about 10 crystals with a purple colour were recovered. We also hoped to sample the barren dike located about 200 m north of the main intrusion. This dike was been reported by Weed (1900) to have the same orientation as the Yogo dike, but different mineralogy and no sapphires. Two shallow pits were found at the approximate location of the dike. Digging to a depth of approximately 2 m in the easternmost pit failed to reach fresh dike rock. Two samples of decomposed rock containing clays and micas were collected from the bottom of the excavation.



Figure 1.3: Photograph showing deep trenches left by mining of the Yogo dike in the early 1900's

Figure 1.4: Photograph of the 1992 working area of Kelly Coulee.

2. REGIONAL AND LOCAL GEOLOGY

2.1 Introduction

The Little Belt Mountains belong to the Central Montana alkalic province which has been described by Pirsson (1900), Larsen (1940), Hearn, Jr. (1989a), and Baker *et al.* (1991). The province includes the following alkaline complexes, from north to south (Figure 2.1): the Sweetgrass Hills (at the northwest corner of Montana), the Bearpaw Mountains, the Little Rocky Mountains, the Missouri Breaks diatremes, Eagle Butte, the Highwood Mountains, the North and South Moccasin Mountains, the Judith Mountains, the Little Belt Mountains, the Castle Mountains, and the Crazy Mountains (Baker *et al.*, 1991; Hearn, Jr. 1989a). The sedimentary rocks in central Montana are predominantly Mesozoic marine and continental clastic deposits and early Cenozoic continental clastic deposits (Hearn, Jr. 1989a). Volcanic rocks occur mainly in the southwest corner of the province and include the Paleocene mafic alkalic Adel Mountain volcanics, the Elkhorn Mountain volcanics (78 Ma), the Cretaceous Maudlow and Livingston volcanics, and the eastern Absaroka belt.

Igneous activity in central Montana occurred from Late Cretaceous to Oligocene (69 to 27 Ma), with two major periods of activity; one between 69 and 60 Ma, and the other between 54 and 50 Ma (Hearn, Jr. 1989a). Flows are preserved only in the Adel, Highwood and Bearpaw Mountains. The onset of igneous activity in Eocene time in Idaho and Montana during the Laramide Orogeny is related to the subduction of the Farallon plate under the lithosphere, producing major uplift and abundant magmatism (Baker, 1994). Eggler and Furlong (1991) calculated the minimum thickness of lithosphere beneath Montana using heat-flow data; they concluded that under the Little Belt Mountains the lithosphere is about 100 km thick. However, seismic-reflection surveys across northern Montana together with seismic-refraction surveys in

north-central and east-central Montana and southern Canada show that the continental crust is about 45 to 50 km thick in central Montana (Hearn, Jr., 1989a).

Deep-source xenoliths (upper-mantle spinel peridotites, deeper upper-mantle garnet-spinel and garnet peridotite) are rare in the alkalic province of central Montana (Hearn, Jr., 1989a). Phlogopite or biotite pyroxenite and wehrlite, phlogopite dunite, and glimmerite xenoliths are abundant locally in the mafic rocks in many of the igneous centers. These common xenoliths are shallow products of the late Mesozoic and Cenozoic magmas; some Mg-rich cumulate xenoliths are likely to be lower-crustal or upper-mantle products of the same magmas (Hearn, Jr., 1989a).

The following section includes a short description of the rock types of the major alkaline complexes of the Central Montana alkalic province; locations are shown on Figure 2.1.

2.1.1 Crazy Mountains

The Crazy Mountains are composed of two series of rocks: silica-saturated or oversaturated, mildly alkalic stocks, and feldspathoidal rocks. The first series include basaltic to rhyolitic rocks. The basalts are more enriched in incompatible elements than typical alkali basalts and are characterized by kaersutite phenocrysts. The second series are variable in composition. The mafic rocks include malignite (mafic nepheline syenite), cumulate malignite, analcime malignite, analcimite, leucite/pseudoleucite malignite, and minette. The felsic alkali rocks are mainly represented by feldspathoidal syenite (larvikite, analcime syenite, pulaskite) and phonolite (Dudas and Eggler, 1989). There are no extrusive rocks in the Crazy Mountains (Larsen and Simms, 1972).



Figure 2.1: Location map of igneous rocks in central Montana, from Hearn, Jr. (1989a).

The Crazy Mountains mafic alkalic rocks are unique in the Montana alkalic province in having $Na_2O > K_2O$. They are unusual even among feldspathoidal rocks because they are strongly enriched in incompatible elements, and have Sr, Nd and Pb isotopic compositions which reflect an ancient source having low Rb/Sr, Sm/Nd and U/Pb ratios (Dudas and Eggler, 1989) The parent magma is also special as it is enriched in barium.

2.1.2 Highwood Mountains, Haystack Butte, Eagle Buttes

Rocks of the Highwood Mountains were emplaced between 54 and 50 Ma. Older quartz-normative latites are intruded by mafic phonolite flows and dikes, minette and trachyte dikes, and shonkinite-mafic syenite stocks (McCallum *et al.*, 1989). The most primitive rocks of the area are olivine minette dikes, and they are probably the parent magma from which the other rock types were derived by fractional crystallization of phlogopite, diopside and olivine (McCallum *et al.*, 1989).

Haystack Butte, located northeast of the Highwood Mountains, is a small Eocene (48 Ma) monticellite peridotite/alnoite intrusion (McCallum *et al.*, 1989). The Eagle Buttes are composed of shonkinite-mafic syenite laccoliths, minette dikes, intrusive breccias and minor latite.

2.1.3 Bearpaw Mountains

Rocks of the Bearpaw Mountains are 54 to 50 Ma old. They are composed of a saturated porphyritic latite group and an undersaturated, mafic to felsic, shonkinite and mafic phonolite group. Intrusive as well as extrusive rocks are represented in the two groups. The main intrusive rocks encountered are shonkinite and syenites, porphyritic latite with minor porphyritic potassic syenite, monzonite and biotite pyroxenite. The extrusive rocks are mainly mafic phonolite, porphyritic latite and minor mafic analcime phonolite and

porphyritic analcime trachyte (Hearn, Jr., 1989b). The Rocky Boy stock shows differentiation from an ultramafic biotite pyroxenite to several variants of shonkinite (pseudoleucite shonkinite, plagioclase shonkinite, hypersthene shonkinite), to nepheline-aegirine syenite, to porphyritic potassic syenite, and to volatile-rich carbonatites (Hearn, Jr., 1989b).

2.1.4 Missouri Breaks Diatremes

These alkalic ultramafic diatremes range in composition from alnoite (melilite-bearing), monticellite peridotite (melilite-free), carbonate-rich mica peridotite, kimberlite, and carbonatites (Hearn, Jr., 1989c).

2.1.5 Judith Mountains

Two periods of igneous activity occurred in these mountains. The first one, between 69 and 67 Ma, produced alkali-calcic rocks while the second one, between 65 and 62 Ma, is responsible for the alkaline rocks. The older group includes quartz monzonite, the intrusive equivalent of quartz latite, monzonite, quartz diorite, diorite, syenite and rhyolite. The second group is composed of mildly alkaline quartz-bearing syenite and strongly alkaline nepheline-bearing tinguaite (Kohrt, 1991).

2.1.6 Little Rocky Mountains

The Little Rocky Mountains are composed of subvolcanic, Paleocene (67 to 61 Ma) felsic porphyritic intrusions.

2.1.7 Castle Mountains

Rocks of the Castle Mountains are predominently felsic in composition, with granite the main rock type. Granite porphyry, quartz-porphyry, rhyolite, and rhyolitic tuffs and breccias are also found (Weed and Pirsson, 1896). Diorite, which grades into quartz-dorite, is the main representative of the mafic rocks and forms a small pluton about 1.5 km in diameter (Weed and Pirsson, 1896). Basalts flows are found in the north in the Volcano Butte area, but these flows are much younger (29 Ma; Irving and O'Brien, 1991) than the core of the Castle Mountains.

2.2 Little Belt Mountain Geology

This mountain belt is formed of Eocene alkaline igneous rocks intruding sedimentary rocks of the Middle Proterozoic Belt Supergroup (see Figure 2.2). Detailed stratigraphic sections with fossil descriptions for many areas of the Little Belt Mountains are given by Weed (1900). Dahy (1988) gives a summary of the sedimentary formations and groups in the Yogo dike area. The geology and petrography of the Little Belt Mountain intrusions were first described by Weed (1900) and Pirsson (1900), respectively. Larsen's (1940) work on the petrographic province of Central Montana includes a short section on the Little Belt Mountains. Geology of sections of the Little Belt Mountains include works by Vine (1956), Witkind (1971, 1973), French (1984), Woodward (1968, 1991), and Embry (1987). More recent studies on the geology of the Little Belt Mountains include Dahy (1988, 1991) and Baker *et al.* (1991).

The Mississippian Mission Canyon Limestone of the Madison group is the main formation to outcrop in the area of the dike. In the easternmost segment of the dike the Kibbey and Otter Formations of the Big Snowy Group (Late Mississippian) are seen. The former outcropped at the Intergem Cut and is composed of a series of red and yellow calcareous sandstones and siltstones with gypsum, carbonate, and shale beds



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Figure 2.2: Geological map of the Little Belt Mountains, from Baker et al. (1991).

14

(Dahy, 1988, 1991). The Otter Formation consists of gray, green and minor black shales and intermittent beds of limestone (Dahy, 1988). It can been seen at the eastern end of the Intergem Cut.

The Belt Supergroup is underlain by Archean metamorphic rocks exposed near Neihart, 24 km to the west of the Yogo dike. This basement complex is composed of gneisses (orthogneiss and paragneiss) and schists of the amphibolite facies (Witkind, 1973). The metamorphic rocks are mantled by some 4,800 feet of sediments in this area (Witkind, 1973) while in the Yogo dike area they are significantly thinner, about 2,000 feet (Dahy, 1988).

The Little Belt Mountains consist of about twenty-five intrusions stretching for a distance of 65 km. The intrusions are dominantly felsic. The Barker porphyry, which is a quartz latite, is an important rock type in the northern section of the Little Belt Mountains as it forms the Barker laccolith, Otter laccolith, Taylor Mountain laccolith, Butcherknife Mountain laccolith, Dry Wolf laccolith, Irene Peak sill, Big Baldy bismalyth, and the Thunder Mountain laccolith (Walker, 1991; Weed, 1900). Other felsic rocks present in this area are the rhyolite porphyry (Walker, 1991) of the Clendennin-Peterson laccolith (55 Ma), the granite porphyry or Wolf porphyry (47.0 Ma) of Mixes Baldy and Anderson Peak, the granite and quartz monzonite of Hughesville stock (45.0 Ma), the rhyolite of the Granite Mountain bismalyth (Walker, 1991), and the syenitic Tillinghast laccolith (Baker et al., 1991; Weed, 1900). Mafic rocks represented as sills, dikes and plugs cutting both sedimentary and igneous rocks in the Barker quadrangle (Witkind, 1971) include shonkinite, plagioclase shonkinite, syenite, minette-kersantite and vogesite. In the south, the major intrusions are composed of shonkinite, monzonite, syenite, and granite. These include the Yogo Peak and Sheep Mountain intrusions (Embry, 1987; Weed, 1900). Minor intrusions include diorite and quartzdiorite porphyry (Weed, 1900), mainly as dikes and sills. Lamprophyres are widespread in the Little Belt Mountains. They occur mainly as sills, and to a lesser extent as dikes. Pirsson (1900) gives a thorough petrographic description of the different types encountered during his mapping. Minette is the most

abundant type. Kersantite and vogesite, which are also classified as shoshonitic or calk-alkaline lamprophyres (Rock, 1977, 1984, 1991), occur locally. Some monchiquites (alkaline lamprophyre) also occur in the Little Belt Mountains. There are only two minor occurrences of effusive rocks or lavas in the Little Belt Mountains, and both of these are basalt (Weed, 1900).

2.3 Yogo Peak

The closest intrusions to the Yogo area are the Yogo Peak intrusion (18.5 kilometres northwest of the dike), and the Sheep Mountain pluton (about 10 km from the dike). The Yogo Peak stock is an elongated intrusion, about 11 km², 6 km long by 0.5 to 2 km wide, trending southwest to northeast (Embry, 1987). It is a composite intrusion composed of shonkinite at its extremities, grading into mafic monzonite, monzonite, syenite and granite towards the centre. Transitions between the rock types are both gradational and irregular (Embry, 1987). The stock intruded the Mississippian Madison limestone at a depth of less than 1200 to 1700 m (Embry, 1987). Embry (1987) observed a continual chemical trend from the most mafic to the most felsic rocks of the intrusion. He proposed that the mixing of a partially crystalline, shonkinitic magma with a partially, or wholly liquid, granitic magma was the mechanism responsible for the following features observed at Yogo Peak: (1) gradational and irregular transitions between rock types; (2) mafic to intermediate xenoliths and xenocrysts in intermediate to felsic rocks; (3) rock type, mineral distribution, and grain-size heterogeneity; (4) co-existence of alkaline and calc-alkaline rocks; and (5) altered olivine with kelyphitic rims in monzonitic to syenitic rocks.

Pirsson (1900) compared the Yogo dike to the minettes and shonkinite of Yogo Peak. He reported that the abundance of biotite showed a relationship to the minettes, but the rock was much richer in ferromagnesian components and lacked feldspar. Despite this, he suggested that the minettes, the shonkinites, and the Yogo dike rock all evolved from the same magma. Dahy (1991) is also in favour of the idea that the Yogo Peak

intrusion and the Yogo dike are genetically related. Marvin *et al.* (1973) reported a K-Ar age of 50.6 ± 1.5 Ma on biotite from the shonkinite of Yogo Peak, and ages of 67.3 ± 2.0 Ma on orthoclase and 50.9 Ma ± 2.0 Ma on biotite from monzonite at Yogo Peak.

Sills of trachyte and rhyolite, and sills and dikes of lamprophyres form a radiating pattern around the Yogo Peak stock for a radius of at least 16 km for the felsic ones and 19 km for the basic ones (Weed, 1900). However, there is no clear physical link between the Yogo stock and the radiating dikes and sills. The lamprophyres are mainly represented by the minette type with a few analcime-basalt (or monchiquite) dikes (Weed 1900; Pirsson, 1900). Cross-cutting relationships between the different intrusions indicate that the youngest dikes and sills are the analcime-basalts, which cut minette dikes, which in turn cross-cut felsic dikes and sills (Weed, 1900). Pirsson (1900) inferred a genetic relationship between the minette sheets and the syenite orthoclase porphyries of Yogo Peak. He suggested that minette, kersantite and vogesite dikes fit petrologically into the plutonic series of the alkaline Yogo Peak.

The Yogo dike is the only representative of the ultramafic lamprophyre type, which is often associated with carbonatites (Rock, 1986). However, no carbonatite are known in the area of the Yogo dike. Dahy (1988) proposed that the Sawmill dome a few kilometers northwest of the dike underlies a carbonatite. Analcime-basalt dikes described by Weed and Pirsson (1896) from Bandbox Mountain (8 km northeast of Yogo Peak), are different from other lamprophyre dikes (and sills) encountered in this mountain belt and have some resemblance to the Yogo dike. The dikes are commonly 0.5 to 1 m. wide, occasionally reaching 3 to 4 m in width. Weed and Pirsson (1896) described the dikes of Bandbox Mountain as augite-minette (or analcime basalt) composed of olivine, augite and mica (phlogopite according to the description) megacrysts lying in a matrix of pyroxene (augite and diopside) and phlogopite. The groundmass was identified as analcime. No feldspar was observed in the rock. This description fits the lamprophyre category and

should be named lamprophyre and not basalt. Pirsson (1900) classified the Yogo dike as a "transition from analcime-basalt to minette".

Although numerous lamprophyre dikes and sills occur in the Little Belt Mountains, only one, the Yogo dike, is corundum-bearing (Weed, 1900; Pirsson, 1900; Clabaugh, 1952). What is even more remarkable, is the fact that, though sapphires are found throughout the entire length of the dike, they do not occur in the parallel dike of nearly similar rock that cuts the limestone 600 feet north of the dike.

2.4 Yogo Dike Geology

2.4.1 Previous Studies

The sapphire-bearing Yogo dike has been the subject of many studies since its discovery at the end of the last century. The first accounts of the Yogo sapphire mine were given by Kunz (1896). In the following year the same author gave a more detailed description of the deposit, accompanied by a petrographic study of the sapphire host rock by Pirsson, and a crystallographic description of the sapphires by Pratt. Further reports were published by Kunz in 1897, 1899, 1900, 1901. Weed (1900) described the geology and the mining activity of the Little Belt Mountains, including the sapphire-bearing Yogo dike. This report was accompanied by petrographic and petrologic studies of the plutonic rocks of this area by Pirsson, also including the Yogo dike. In 1952, Clabaugh published a compilation of corundum deposits of Montana, with an extensive description of the Yogo mine and including a chemical analysis of the rock. This is the only chemical analysis of the dike rock published to date. Clabaugh (1952) emphasized the enormous economical potential of the deposit as the dike extends downwards for several thousand feet. Meyer and Mitchell (1988) published chemical analyses of the main minerals and reviewed the classification of the rock. The Yogo dike has been described (by Kunz, 1896; Pirsson, 1900; Clabaugh, 1952) as an analcime

basalt, bearing some resemblance to minette and monchiquite (Pirsson, 1900) and ouachitite (Clabaugh, 1952). Meyer and Mitchell (1988) reclassified the rock as an *ouachitite*, based on Rock's (1986) classification of ultramafic lamprophyres.

The Yogo dike and area were mapped in detail by Dahy (1988), who also provided petrographic descriptions of the rocks (1988, 1991). Other publications on the Yogo deposit include Baron (1982), Zeihen (1987), Brownlow and Konorowski (1988), and Voynick (1985). The latter author provided a very interesting account of the history of the Yogo mine in his book "Yogo the Great American Sapphire".

2.4.2 Yogo Dike Description

Dahy's work (1988, 1991) was of great use in that it included a detailed geological map of the dike. Since the dike is mined out for almost its entire length, the present work would have been impossible without a base map (see Figure 2.3, inside the back cover).

The dike is about 9 km long and is composed of three *en echelon* segments trending N75E, each segment terminated in its western end by a sapphire-bearing breccia, called a diatreme by Dahy (1988). The dike is nearly vertical and varies in width from 0.5 m at the east gate to 6 m at the English Mine (Clabaugh, 1952; Dahy, 1988, 1991). The easternmost segment is called the Intergem Cut, the middle one is composed of the English Mine to the east and the Middle Mine at its western end, and the third segment is referred to as the American Mine. The dike extends westward into Kelly Coulee where mining was conducted in 1992 and into the limestone cliffs north of Kelly Coulee where it was mined by Vortex in the late 1980's. The dike is only half a meter wide in this area.





During field work fresh rock was observed only at the Middle Mine from the previous season of mining, and in the dump of the English Mine. The easternmost segment (the Intergem Cut) was filled in due to land reclamation laws. The lower part of the English Mine cut was accessible in some areas but was covered by limestone blocks detached from the walls. At Kelly Coulee the rock is altered to ochre-coloured clays in which numerous limestone xenoliths and weathered dike xenoliths can be observed. Earlier writers (Pirsson, 1900; Weed, 1900) described the appearance of the dike on surface at the English Mine:

"Near the surface it (the Yogo dike) consists of a coarse breccia of limestone and shale fragments cemented by the igneous rocks. Where the upward termination of the dike is seen, at the westernmost workings, the top part of the dike is a blunt wedge and the material consists chiefly of these rock fragments. This is believed to be the fragmental material from the fissure walls, which has been floated upward as the molten rock rose in the fissure, like chips on the surface of a stream of water. The workings were in 1897 entirely in altered rock, the shaft being at that time only 60 feet. At this depth it had passed out of the zone of surface alteration, and the ocherous, yellow clay was replaced by a blue clay which reminds one very much of the description given of the Kimberley diamond matrix. The upper part of the dike is largely a brecciathat is, it consists of a mixture of dike material and the limestone fragments. It appears to be somewhat near the apex of the dike."

This description seems to be applicable to the rock at Kelly Coulee. Dahy (1988) mapped the area as a diatreme, but the alteration and look of the rock could also be due to natural weathering of the rock exposed to elements.

Although studies on the Yogo dike deposit are numerous, the lamprophyre has not been petrologicaly characterized in great detail, as is the case for many other ultramafic lamprophyres.

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The Yogo dike has no chemical equivalent amongst the rocks of the Little Belt Mountain. Some lamprophyre dikes from the Bandbox Mountain described by Pirsson (1900) as analcite basalt have some chemical similarity with the Yogo dike. The rock is however significantly richer in silica (48.3 wt.% SiO₂), and poorer in Ca (7.6 wt.% CaO) than the Yogo dike (38.3 to 40.43 wt.% and 15.4 to 18.4 wt.%, respectively) but more mafic than the numerous minette sills and dikes encountered in the area. One lamprophyre dike described by Weed and Pirsson (1896) from the Castle Mountains is very similar in composition to the Yogo dike; in fact, no other rocks in the Little Belt Mountain or the Castle Mountains (only 50 km south) have such a similar composition. These authors described the rock as being black and heavy and containing crystals of yellow olivine. It consists chiefly of augite, and is related to the monchiquites. The major differences between this rock and the Yogo dike is its higher silica and titanium contents (Table 2.1), and lower CaO and CO₂ contents. Chemically, the rock has characteristics of both alkaline and ultramafic lamprophyres. Its silica content is more toward the AL lamprophyre field while its Mg content is more toward the ultramafic lamprophyre trend.

	Yogo Dike average (Carleton)	Yogo Dike Average (XRAL)	Average Ouachitite	Average Monchiquite	Analcime- basalt	Monchiquite (?)
Samples	6	6	36	239	1	1
SiO ₂	39.64-40.43	38.80-39.80	36.50	41.2	48.39	42.46
Al_2O_3	10.62-12.53	10.20-12.00	9.10	13.3	11.64	12.04
Fe ₂ O ₃	6.79-7.55	6.72-7.53	13.20	12.0	4.09	3.19
FeO	n.d.	3.20-3.50	n.đ.	n.d.	3.67	5.34
MgO	11.04-11.85	10.80-11.40	11.40	8.2	12.55	12.4
CaO	16.62-18.40	15.40-16.70	13.40	11.0	7.64	12.14
Na ₂ O	0.73-2.02	0.83-1.95	1.70	3.0	4.14	1.21
K ₂ O	2.10-2.45	2.04-2.44	2.10	2.0	3.24	2.68
TiO ₂	1.00-1.04	0.95-0.99	2.80	2.7	0.73	2.47
P_2O_5	1.14-1.23	1.15-1.24	1.10	0.84	0.45	0.84
MnO	0.13-0.15	0.13-0.15	0.19	0.2	trace	0.16
H_2O^+	n.d.	2.00-3.40	3.20	3.3	2.56	4.03
H_2O^-	n.d.	0.30-1.30	n.d.	n.d.	0.28	n.d.
BaO	n.d.	n.d.	n.d.	n.d.	0.32	n.d.
SrO	n.d.	n.d.	n.d.	n.d.	0.15	n.d.
CO,	n.d.	3.48-4.75	4.50	1.5	none	0.55
S	n.d.	n.d.	0.22	0.06	n.d.	n.d.
Ba	3554-4083	3140-3440	950	1025	n.d.	n.d.
Cr	730-973	0.09-0.12ª	263	240	n.d.	n.d.
Sr	1425-1955	1410-1910	1300	1100	n.d.	n.d.

Table 2.1: Comparison between Yogo dike analyses, average ouachitite and monchiquite (Rock, 1991), the analcime-basalt dike of Bandbox Mountain (Pirsson, 1900) and a "monchiquite" dike in the Castle Mountains (Weed and Pirsson, 1896). All analyses are in wt.% except for trace elements which are given in ppm. The Yogo dike averages include three samples from the Middle Mine and three samples from the English Mine.

^aWt.%.

3. PETROGRAPHY

The Yogo dike rock has been described by Meyer and Mitchell (1988) and Rock (1987) as an ouachitite of the ultramafic lamprophyre group, and more recently as a damkjernite (Rock, 1991). The classification of the rock will be discussed in more detail in the chapter on geochemistry.

In hand specimen the English Mine rock is greenish grey on its patina and dark grey on a fresh surface. Middle Mine samples are fresher and are usually dark grey to slightly greenish grey in colour. Samples from these two localities have the characteristic glistening appearance of lamprophyres, due to numerous phlogopite plates up to 1 cm across (but generally less then 1 or 2 mm). The rock is fine grained to aphanitic. With the naked eye it is possible to see mica plates, round to elliptical white ocelli, numerous xenoliths and occasional sapphires. With a hand lens one can identify green prismatic pyroxene crystals.

Samples from Kelly Coulee are composed mainly of ocre, yellow, and brick-red clays with embedded limestone clasts. The samples are soft and can be broken by hand. Samples from the Intergem Cut have a similar appearance to samples from Kelly Coulee, but are mainly brick-red in colour.

About 70 polished sections from the Yogo deposit were studied in the course of this project. Each section is described in Appendix D. Samples from which thin sections were not made are briefly described in the same appendix. The rock has a porphyritic texture (Figure 3.1). It is composed of phlogopite and clinopyroxene (augite, diopside) megacrysts set into a matrix of phlogopite and clinopyroxene grains with interstitial analcime, calcite, magnetite, and apatite. The rock contains no orthopyroxenes. Accessory minerals include corundum and pleonaste ((Mg,Fe)Al₂O₄). The rock also contains globular structures called ocelli composed of zeolites, carbonates with accessory barite, and opaque minerals (generally pyrite). Some ocelli contain green laths and prisms of amphibole. Large crystals (1 to 1.5 cm long), altered to



Figure 3.1: Photograph of the Yogo dike rock showing the porphyritic texture. The field of view is approximately 2.5 mm.
serpentine, talc, and chromite, are quite common in the rock. The crystals are elongated prisms doubly terminated by pyramids which suggests that they might be pseudomorphs after olivine.

The mode of the main phases present in the sections studied is given in Appendix D. Each mineral and feature present in the rock (e.g. xenolith, ocelli) will be described in detail in the section below.

3.1 Pyroxenes

The rock contains only clinopyroxenes and no orthopyroxenes. The former is the main mineral phase forming the Yogo dike rock. In thin section the clinopyroxene appears as pale yellow to colourless grains (diopside) and pale green grains (augite). In cross section the crystals show the characteristic ~90° cleavage angle of clinopyroxenes. Clinopyroxenes in the matrix are euhedral and subhedral prisms, 0.1 to 0.5 mm long. Clinopyroxene megacrysts range in size from 0.5 mm to 1.5 cm. These are called megacrysts and not phenocrysts because the genetic relationship with the host rock is uncertain, and some may be xenocrysts while others may be phenocrysts. In crossed-polarized light it is apparent that all of the pyroxenes are zoned. Megacrysts can have up to 15 rims (Figure 3.2a) but usually have less than five. Matrix clinopyroxenes usually have only one or two rims but occasionally have as many rims as the megacrysts (Figure 3.2b). The external rims of megacrysts and matrix pyroxenes contain apatite inclusions. Pyroxene grains are usually fairly fresh, but some are partially altered to carbonates, amphibole, and serpentine minerals.



Figure 3.2(a): Photograph of rims on a pyroxene megacryst (approximately 2 mm long).



Figure 3.2(a): BSE image of a matrix pyroxene.

3.2 Phlogopite

Like clinopyroxenes, phlogopite occurs both as megacrysts and as groundmass grains. Phlogopite in the matrix ranges in size from 0.1 to 0.5 mm, and is usually between 0.2 and 0.4 mm. It is subhedral to euhedral. Phlogopite megacrysts are 0.5 mm to up to 1 cm long, but are usually less than 4 mm in length. Megacrysts are strongly pleochroic and are always zoned. Many rims can be discerned on some of the largest megacrysts (Figures 3.3a, b). Core zones are colourless when the *c* axis of the crystal is horizontal and pale brown when the stage is turned 90° from this position. The pale colour of the cores indicates that the phlogopite is rich in Mg. Phlogopite cores always have an elliptical outline indicating corrosion of the crystals during transport to the surface. The rims are orange brown (Fe-rich phlogopite to biotite) and corroded with embayments. The external rims often contain euhedral apatite inclusions (0.01 to 0.05 mm) while the cores of large megacrysts are rich in clinopyroxene and some carbonate inclusions. Some phlogopite crystals have inclusions of dark green spinel (pleonaste), which is sometimes rimmed by magnetite. The mica adjacent to pleonaste is dark brown (Fe-rich phlogopite or biotite) indicating a possible Mg (and Al) exchange between the spinel and the host phlogopite.

3.3 Magnetite

The groundmass spinel in the Yogo dike is magnetite. It is distributed throughout the matrix as subhedral grains (0.01 to 0.1 mm in size, averaging 0.04 mm). Magnetite also occurs as rims around pleonaste spinel (see below). The core is often a mixture of magnetite and quartz which, together with the small size of the grains, creates analytical problems. Magnetite also occurs as a discontinuous rim around the sapphires, in which case Al-Mg-Fe spinel is sandwiched between the two.

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Figure 3.3 (a): Photograph of a phlogopite megacryst (approximately 2 mm long).



Figure 3.3 (b): BSE image of phlogopite megacrysts.

3.4 Apatite

Apatite is a common accessory mineral in the Yogo dike, forming 2 to 3% of the rock. Apatite occurs in the matrix as subhedral to euhedral grains less than 0.2 mm long. It is a very common inclusion in phlogopite and pyroxene external rims, and is seen in just about every crystal. (Figure 3.4).

3.5 Ocelli

Ocelli have a round to elliptical outline and range between a few millimeters to 1.5 cm across. Two types have been recognized; one type composed of zeolites and carbonates with accessory barite and the other with carbonates, analcime and green amphibole. Ocelli are distributed heterogeneously in the rock; some samples have up to 15% ocelli while others have none.

Backscattered imaging of the ocelli reveal that they are zoned. The core is composed of calcite which is rimmed by dolomite and then by analcime. The core often contains barite grains as inclusions (Figure 3.5).

3.6 Xenoliths and Autoliths

The Yogo dike rock contains numerous xenolithic inclusions as well as autoliths or cognate xenoliths. They are a few millimeters to up to 4 cm in length. They can be divided into 3 groups according to their depth and relation with the host rock: (1) upper crust xenoliths such as limestone clasts, granitic xenoliths, gneisses; (2) lower crust xenoliths such as high grade metamorphic xenoliths (kyanite-garnet xenolith,



Figure 3.4: SEM micrograph showing pyroxenes and phlogopites with apatite inclusions.



Figure 3.5: BSE image showing barite grains in ocelli.

garnet-pyroxene-plagioclase granulite xenolith, mafic amphibole-pyroxene-phlogopite xenolith) and, (3) cognate xenoliths or autoliths (clinopyroxenites and phlogopite clinopyroxenites).

The last two groups are the most important in unraveling the history of the Yogo dike. Xenoliths belonging to the second group are relatively rare relative to the ones from the other two groups. Only two xenoliths that are thought to come from the lower crust were found: a garnet-pyroxene-plagioclase granulite xenolith and a mafic amphibole-pyroxene-phlogopite-(spinel) xenolith. Xenoliths described in the literature but not found during the study include a kyanite-quartz xenolith (Clabaugh, 1952), a kyanite-garnet-quartz xenolith (Dahy, 1991) and a plagioclase-pyroxene-corundum xenolith (Dahy, 1991).

3.6.1 Autoliths or Cognate Xenoliths

The most obvious inclusions present in the Yogo dike are bright apple-green clinopyroxenites, which sometimes occur with coarse phlogopite grains. Many of these clinopyroxenite inclusions have been studied in thin section. They have a very simple mineralogy: medium to coarse grained euhedral clinopyroxene (0.5 to 5 mm) and euhedral phlogopite. These two minerals look very similar to many of the megacrysts found in the rock and probably have a similar origin. They are probably cumulate phases crystallized in the magma chamber prior to eruption of the magma to the surface. Pyroxene and phlogopite in the clinopyroxenites do not have the thin external rim rich in apatite inclusions present on all the megacrysts. Only the crystals forming the perimeter of the autolith have this rim. One of these cognate xenoliths was found partially enclosing a sapphire. The sapphire has a pleonaste rim and is surrounded by coarse phlogopite (~2 to 3 mm).

3.6.2 Garnet-Clinopyroxene-Plagioclase Granulite Xenolith

This xenolith measures 1 by 3 cm. In hand specimen, one can see red grains (garnet) smaller than a millimeter in diameter. In thin section the xenolith is composed of small (<0.5 mm) garnets with interstitial clinopyroxene (<0.4 mm) and a few plagioclase crystals (<0.2 mm; Figure 3.6). The garnets have a green rim of kelyphite of unknown composition. Some garnets are totally converted to this retrograde alteration. The xenolith has a reaction rim of green pleonaste. This xenolith is interesting because the garnet-clinopyroxene-plagioclase association permits estimation of the depth and temperature of formation of the xenolith and thus minimum conditions for the Yogo dike. This will be discussed later in the chapter on geothermobarometry.

3.6.3 Mafic Amphibole-Clinopyroxene-Phlogopite-(Spinel) Xenolith

This xenolith measures approximately 4 cm in length. It is composed of coarse grained (0.5 to 3 mm) brown amphibole (possibly kaersutite or barkevikite), clinopyroxene and phlogopite. Pyroxenes are weathered and associated with secondary pleonaste spinel.

3.7 Accessory Minerals

3.7.1 Sapphire

Corundum (sapphire) is an accessory mineral in the rock. It always has a corroded outline, sometimes with numerous embayments indicating that it was in disequilibrium with the magma at the time of dike emplacement. All of the sapphire observed *in situ* in the ouachitite have rims of pleonaste spinel (Figure 3.7). However, sapphires found *in situ* in the altered rock at Kelly Coulee do not have pleonaste rims.



Figure 3.6: Photograph of a garnet-clinopyroxene-plagioclase granulite xenolith.



Figure 3.7: Photograph of a sapphire rimmed by black pleonaste spinel.

Under the microscope or in a backscattered image the sapphires show no apparent zoning.

3.7.2 Pleonaste Spinel

A common accessory mineral present in the Yogo dike is green pleonaste (aluminous spinel), often associated with magnetite. Although present as less than one percent of the rock, it is easily detected in thin section due to its green colour. Green spinel occurs in four associations: (1) as grains inside phlogopite, (2) as euhedral to subhedral grains associated with clinopyroxenes from xenoliths, (3) as discrete grains in matrix, and (4) as rims around all sapphires observed in the ouachitite.

Pleonaste spinel is usually found in high grade metamorphic rocks derived from aluminous sediments and its association with an ultramafic lamprophyre is quite unusual. Green pleonaste spinel has also been observed in lamproites as inclusions in phlogopite or leucite (Wagner *et al.*, 1987; Mitchell and Bergman, 1991). These aluminous spinels are believed by Mitchell and Bergman (1991) and Chapman (1975) to be secondary and to have formed by either exsolution or reaction processes. Mitchell and Bergman (1991) proposed that the aluminous spinels observed in the West Kimberley lamproites as inclusions in leucite originated by exsolution from a non-stoichiometric leucite containing Mg, Fe, and Ti in solid solution. Grapes (1986) described the occurrence of green spinel (pleonaste) as decomposition products of biotite. Brearley (1987, 1986) and Brearley and Rubie (1990) studied the pyrometamorphic breakdown of Fe-Al biotite into Mg-Al biotite + magnetite + hercynite spinel + K-feldspar/melt + vapour. He also observed that an increase in the Mg number of biotite produces an increase in the Mg number. The occurrences of pleonaste spinel found in the Yogo ouachitite will be described in detail below, as it might be associated with corundum in the dike (corundum-bearing rocks usually contain spinel) and so could shed some light on the presence of corundum in the rock.

Pleonaste Associated with Phlogopite

This a frequent association. Pleonaste observed in phlogopite is surrounded by a halo of biotite (orange brown; Figure 3.8a). Magnetite usually rims pleonaste but not always. Pleonaste has also been observed associated with biotite after pyroxene.

Pleonaste spinel commonly occur as inclusions in subhedral to euhedral phlogopite megacrysts, usually rimmed by magnetite. Phlogopite hosting pleonaste spinel are often pale in colour suggesting a high Mg content and they are undifferentiable from phlogopites that do not host spinel. Spinels are unrimmed or very thinly rimmed in the last association. Another common occurrence of pleonaste spinel is with xenomorphic phlogopite in the matrix. It is often rimmed by magnetite. Spinel found in phlogopite is rarely euhedral, although some have been found with a euhedral habit. These phlogopite crystals are thought by the author to be cumulate phases crystallized around the magma chamber. One of the samples (42-a) is particularly interesting. A phlogopite megacryst hosting a green spinel is rimmed by a more Fe-rich phlogopite (based on the colour of the phlogopite). Part of the spinel is in the phlogopite core and part in the rim. The spinel portion in the rim is rimmed by magnetite while the portion in the phlogopite core is unrimmed. This feature suggests that the spinel appeared after the phlogopite grain (Mg-rich core rimmed by Fe-rich rim) finished crystallizing.

Pleonaste Associated with Clinopyroxenes

Pleonaste occurs on some clinopyroxene megacrysts and interstitially to pyroxene grains in some clinopyroxenites. They are occasionally mantled by a thin rim of magnetite. When pleonaste is present, the clinopyroxene is always weathered. The clinopyroxene megacrysts hosting pleonaste are very similar to those hosting pleonaste in the clinopyroxenite and it can be inferred that they have a similar composition. Such occurrences of pleonaste in clinopyroxenes or interstitial to clinopyroxenes have



Figure 3.8 (a): BSE image showing a pleonaste grain (medium grey) in phlogopite (pale grey). The bright spots around the pleonaste is magnetite.



Figure 3.8 (b): Pleonaste interstitial to pyroxenes from a xenolith.

been described by Chapman (1975). He suggested that pleonaste exsolved from the aluminous pyroxenes.

Spinel associated with pyroxenes are usually large (up to 1 mm) and subhedral to euhedral (Figure 3.8b). Pleonaste also occurs in a kaersutite-pyroxene-phlogopite xenolith, as euhedral to sub-euhedral grains less than 0.5 mm long, and mainly associated with pyroxene. When on or interstitial to pyroxenes, pleonaste is unrimmed. It is rimmed by magnetite when in contact with the matrix. In some instances there is another mineral, perhaps chlorite, between the spinel and the magnetite rim.

Pleonaste as Discrete Grains in Matrix

In the matrix, pleonaste occurs as anhedral to euhedral grains (0.1 to 0.2 mm) always rimmed by magnetite (Figure 3.9). The thickness of the rim varies. They are rarely euhedral. They are easily recognized under the microscope due to their contrasting colour. Also seen in the matrix are magnetite rims surrounding an almost perfectly isotopic pale green mineral resembling Mg-rich chlorite. It is uncertain if this mineral is the result of spinel alteration or if it is a transitional phase between the mineral it is after and pleonaste.

Pleonaste as Rims on Sapphires

All sapphires encountered *in situ* are rimmed by pleonaste spinel, which in turn is rimmed by magnetite. The rim is dark gray on a macroscopic sample and dark green to black seen under microscope. The composition and morphology of these rims has been studied using an electron microprobe. The spinel is Al-Mg-Fe pleonaste and is similar to the spinel described earlier. The composition of the rim will be discussed in detail in Chapter 6.2.



Figure 3.9 (a): Pleonaste grain in matrix.



Figure 3.9 (b): BSE image of a pleonaste grain (grey) rimmed by magnetite (white).

The most striking characteristic of all the sapphires observed is their high degree of corrosion. Sapphires reacted with the magnesian magma to form pleonaste spinel. Some sapphires are almost completely dissolved while others are only slightly corroded. The thickness of the rim is variable. Pleonaste rims can locally be as thick as 0.5 mm, with islands of sapphire in the spinel rim (Figure 3.10). The spinel rim is mantled by a magnetite rim. Where the spinel rim is relatively thick, the magnetite rim is almost non-existent. In cases where the spinel rim is very thin, magnetite is more abundant. The varying thickness of the spinel rim suggests that the sapphires have been in contact with the magma for different lengths of time. This feature suggests that the sapphires are xenocrystic and that they were incorporated into the magma when corundum-bearing xenoliths disintegrated. According to this scenario, the sapphires would be in contact with the magma for varying periods of time and this would explain the different spinel rim thicknesses. If the sapphires were phenocrysts, they would have formed at about the same time and then been subjected to the same period of time in the magma.

3.7.3 Cr-Al Spinel

Chrome-spinel were found in the ouachitite, but only as secondary phases. They occur on large partially serpentinized megacrysts and in partially weathered pyroxenes of phlogopite pyroxenite. It is uncertain if the Cr-spinel are secondary in this last occurrence.



Figure 3.10 (a): BSE image of a sapphire (same as in Figure 3.7) showing thin discontinuous pleonaste and magnetite rims.



Figure 3.10 (b): BSE image of a sapphire (dark grey) with a thick pleonaste rim (medium grey). There is very little magnetite (white) on this grain.

4.1 Introduction

All previous studies have ignored the age of the dike, as it was presumed to be related to the numerous Eocene intrusions in the Little Belt Mountains. However, since it is the only ultramafic lamprophyre in the area, and there is no proof of a genetic relationship with any of the other intrusions, precise dating of the dike was deemed essential.

Dating methods applicable to the Yogo dike are quite limited. Ultramafic lamprophyres do not contain significant amounts of U- and Pb-bearing minerals (such as zircon, monazite, and perovskite). This prevents use of the U-Pb system, which is the most popular and precise method available today. Perovskite is occasionally a minor accessory mineral in ultramafic lamprophyres, but was not found in the Yogo intrusion. Petrographic and field evidence for extensive incorporation of crustal rocks into the magma indicated that Sm-Nd and/or Rb-Sr whole rock dating methods would be inapplicable. Lamprophyres contain abundant micas, which are rich in Rb and K, and therefore Rb-Sr and K-Ar methods on phlogopite were considered. Very high and erratic measured Rb/Sr ratios in several phlogopite separates precluded the use of Rb-Sr methods to date the rock.

4.2 K-Ar Systematics

Potassium has three naturally-occurring isotopes: ³⁹K (93.2581%), ⁴⁰K (0.01167%), and ⁴¹K (6.7302%). ⁴⁰K is radioactive and decays to the stable isotopes ⁴⁰Ca and ⁴⁰Ar (11.2%), with a decay constant of 4.962 $\times 10^{-10}$ yr ⁻¹ (Hanes, 1991). ⁴⁰Ar produced by radioactive decay of ⁴⁰K is trapped in the lattice of the mineral host. Since argon is a gas, none is absorbed into the crystal lattice of a K-bearing phase during crystallization during crystallization of the mineral. The age of the mineral is given by the following equation:

$$t = 1 / \lambda ({}^{40} \operatorname{Ar} * / {}^{40} \operatorname{K} (\lambda / \lambda e) + 1)$$

where λ is the total decay constant; λe is the decay constant of ⁴⁰K to ⁴⁰Ar, and ⁴⁰Ar* is the radiogenic ⁴⁰Ar produced by decay of ⁴⁰K.

4.3 Sample Preparation

A sample of dike material weighing approximately 10 kg was carefully cleaned and weathered surfaces were removed. The sample was reduced to fine sand size using a jaw crusher and disc grinder. The ground sample was then passed over a wet shaking (Wilfley) table, and a heavy concentrate was recovered. A mica-rich fraction was also recovered from the Wilfley table. The mica concentrate was sieved to obtain a 40 to 60 and a 60 to 80 mesh fraction. These were washed in dilute (6N) HCl to dissolve contained carbonate, and were then concentrated to 100% purity using an inclined vibrating table and hand methods.

The heavy mineral separate from the Wilfley table was further processed by sieving out the >60 mesh fraction and passing the finer fraction through methylene iodide ($\rho = 3.3$). The heavy fraction was then split into several fractions based on differing magnetic susceptibilities, using a Frantz Isodynamic magnetic separator, first in free-fall and then in ramp mode. Table 4.1 shows the fractions recovered by varying the current from 0.2 to 1.8 A. Minerals were identified using backscattered images on the electron microprobe.

Fraction	Minerals
Magnetic at 0.2 A	pyroxenes, Al-Mg-rich magnetite, Fe-Mn oxides, sapphires
0.4 A	diopside, Mg-Fe carbonates, pyroxene with magnetite inclusions, pyrite, Al-Cr-Fe-Mg spinel
0.6 A	diopside, Al-Fe-Mg spinel
1.0 A	pyroxenes, pyrite
1.2 A	not analyzed
1.6 A	diopside, pyrite, Ca-Mg-Fe carbonate, dolomite, pyrite, sapphire, rutile, titanite
1.8 A	sapphire, diopside, pyrite
Non-magnetic at 1.8 A	not analyzed

 Table 4.1:
 Mineral composition of magnetically-separated fractions.

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4.4 Results

K concentrations for samples submitted for K-Ar analyses were determined by first dissolving the mineral concentrate in concentrated HF and HNO₃, and then analysing the solution using conventional atomic absorption flame photometry and internationally recognized standards. Ar isotopic compositions were measured on a modified MS-10 mass spectrometer. All analytical errors were propogated through the age calculation and the final age is reported with errors at the 2σ level.

The K-Ar date obtained from phlogopites in the dike is 48.2 ± 1.3 Ma. K-Ar dating of 30 intrusions in the Little Belt Mountain by Marvin *et al.* (1973) indicates that they were emplaced between 41.2 ± 1.5 M.a. and 57.8 ± 2.2 Ma, with a peak in plutonism between 48 and 54 Ma. Most of the dates were obtained on biotite, some on whole rock and one date (57.8 ± 2.2 Ma) on hornblende. The result for the Yogo dike indicates that it was emplaced at the same time as the major intrusions of the Little Belt Mountain. The shonkinite of Yogo Peak yielded an K-Ar age on biotite of 50.6 ± 1.5 , while the monzonite yielded 50.9 ± 2.0 (Marvin *et al.*, 1973). Statistically, the Yogo Peak intrusion and the Yogo dike were emplaced at the same time.

5. WHOLE ROCK GEOCHEMISTRY

Six samples were analyzed for major and trace elements; three from the Middle Mine and three from the English Mine. Samples were analyzed in duplicate; one set was sent to Carleton University and analyzed by R. Taylor and one set was sent to XRAL Laboratories in Toronto. XRAL analyzed major elements (SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, K₂O, TiO₂, P₂O₅, Cr₂O₃, MnO) by X-ray fluorescence using fused discs. H₂O⁺, H₂O⁻, F, and FeO were analyzed by wet chemistry, and CO₂ by the COULOM method. Trace elements (Rb, Sr, Y, Zr, Nb and Ba) were analyzed by XRF using pressed pellets. At Carleton University, major and trace elements were analyzed by XRF using fused discs. A duplicate of every sample was run. Gravel-size samples were ground to powders using an agate mortar to reduce contamination. Trace elements (V, Cr, Co, Ni, Zn, Rb, Sr, Y, Zr, Nb, Ba, La, Ce, Nd, Pb, Th and U) were also analyzed by XRF using fused discs.

5.1 Sample Preparation

The weathered surface of the samples was removed using an hydraulic splitter. Large xenoliths present in the rock were also removed from the fresh rock using the same equipment. Compressed air was then used to remove dust coating the fragments. These were then crushed to coarse gravel size (1.5 to 2.5 cm) using a pre-contaminated jaw crusher. Gravel fragments containing xenolith fragments were rejected and the samples were crushed to a smaller size (< 1.5 cm). Two of the samples sent to XRAL were ground to a powder using a tungsten carbide disc mill (shatter box). The other samples were sent as gravel-size separates (< 1.5 cm).

The analyses are presented in Table 5.1. By comparing the average analyses from Carleton and XRAL, we note that the Carleton analyses are higher for four major elements: SiO_2 (0.20 to 1.33 wt.% higher), CaO (1.45 to 3.10 wt.% higher), Al₂O₃ (0.23 to 0.53 wt.% higher), MgO (0.24 to 0.46 wt.% higher). The Carleton analyses are also higher for Ba and Sr by 300 to 650 ppm and 5 to 81 ppm, respectively, while Zr analyses are significantly lower by 76 to 95 ppm.

The main geochemical characteristics of the Yogo dike are the following: it is silica poor (~40 wt.% SiO₂), Ca-rich (up to 18.4 wt.% CaO), Mg-rich (~11 wt.% MgO), Ba-rich (3000 to 4000 ppm), Sr-rich (1400 to 1950 ppm), Cr-rich (up to 973 ppm), reflecting the association between ultramafic lamprophyres and carbonatites. K_2O/Na_2O (molar) ratios vary between 0.78 and 0.84 for the Middle Mine samples and between 1.03 and 1.93 for the English Mine samples. According to the definition of potassic rocks $[K_2O/Na_2O$ (wt.% or molar) > 1], the English Mine samples are potassic while the Middle Mine samples are not. The calculations have been done on a molar basis which better reflects the mineralogy of the rock than do wt.% ratios, which are greater than 1.0 when done on a wt.% basis. The alkalinity of the Yogo dike was assessed using the following scheme, from Mitchell (1991): an alkaline rock is one in which the alkalies are in excess of the alkali feldspar molecular ratio [(Na₂O + K₂O) : Al₂O₃ : SiO₂] of 1:1:6, with either Al₂O₃ or SiO₂ being deficient. The Yogo dike has ratios of about 1:2:12 and with respect to this definition is not alkaline. The rock is neither quartz nor nepheline (or leucite) normative, reflecting a transition between silica-undersaturated and silica-oversaturated rocks. The norm was calculated to determine whether the Yogo magma is corundum normative. The norms are presented in Table 5.2 and show that the rock is not corundum normative

(0/114	MM1	MM2	MM3	AVE (M.M)	EM1	EM2	EM3	AVE (E.M) +
				+ lσ				lσ
SiO ₂	39.64	40.11	40.39	40.04 ± 0.38	39.91	39.65	40.43	39.99 ± 0.39
TiO ₂	1.01	1.04	1.01	1.02 ± 0.02	1.01	1.02	1.00	1.01 ± 0.00
Al_2O_3	10.62	12.24	12.53	11.79 ± 1.03	11.11	11.57	11.54	11.40 ± 0.25
FeO	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Fe ₂ O ₃	6.79	7.36	7.45	7.20 ± 0.36	7.55	6.99	7.26	7.26 ± 0.28
MnO	0.13	0.14	0.14	0.14 ± 0.00	0.14	0.13	0.15	0.14 ± 0.00
MgO	11.76	11.04	11.26	11.35 ± 0.37	11.85	11.20	11.21	11.42 ± 0.37
CaO	18.16	16.92	16.62	17.23 ± 0.81	18.40	17.50	16.77	17.55 ± 0.82
Na ₂ O	1.71	1.86	2.02	1.86 ± 0.16	0.73	1.57	1.37	1.22 ± 0.44
K ₂ O	2.10	2.36	2.18	2.21 ± 0.13	2.45	2.37	2.33	2.38 ± 0.06
P_2O_5	1.23	1.15	1.14	1.17 ± 0.05	1.18	1.20	1.18	1.19 ± 0.00
Cr_2O_3	0.28	0.23	0.23	0.25 ± 0.03	0.23	0.22	0.21	0.22 ± 0.00
H_2O^+	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
H_2O^-	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
CO ₂	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
F (ppm)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
LOI	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
TOTAL	93.13	94.19	94.73	94.01	94.32	93.18	93.22	93,57
V	141	156	152	149 ± 7	148	150	152	150 ±2
Cr	973	787	783	848 ± 108	784	746	731	753 ± 27
Со	34	38	36	36 ± 2	32	45	37	38 ± 7
Ni	230	209	218	219 ± 11	212	208	203	208 ± 5
Zn	68	71	72	70 ± 2	74	104	80	86 ± 16
Rb	79	98	93	90 ± 10	62	75	78	72 ± 8
Sr	1782	1701	1706	1729 ± 45	1428	1830	1950	1736 ± 274
Y	16	17	17	17 ± 0	18	17	18	18 ± 0
Zr	198	206	207	203 ± 5	207	208	215	210 ± 4
Nb	64	71	75	70 ± 6	71	72	83	75 ± 7
Ba	3871	4080	4081	4011 ± 121	3647	3714	3559	3640 ± 77
La	139	148	164	150 ± 13	143	151	201	165 ± 31
Ce	294	310	328	310 ± 17	298	313	458	356 ± 88
Nd	126	141	135	134 ± 8	119	131	171	140 ± 27
Pb	29	29	35	31 ± 3	30	24	32	29 ± 4
Th	11	13	13	12 ± 1	13	13	14	13 ± 0
U	11	10	10	10 ± 0	10	11	12	11 ± 1
mg = Mg/(Mg)	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
+ Fe _{total})								
K/(K + Na)	0.45	0.45	0.42	0.44 ± 0.02	0.69	0.50	0.53	0.57 ± 0.10
K ₂ O/Na ₂ O	0.81	0.84	0.71	0.79 ± 0.07	2.21	0.99	1.12	1.44 ± 0.67
(molar)								

Table 5.1: Chemical analyses of Middle Mine and English Mine samples, done at Carleton University (oxides in wt.%, traces in ppm).

14010 5.1. (010)	MM1	MM1 MM2 MM3 AVE (M.M) FM1 FM2		FM2	FM3	$\overline{AVE(E.M)}$ +		
	1411411	1011012	1011010	+ lo	LAVIT	1.1112	121013	1σ
SiO ₂	38.80	39.70	39.80	39.43 ± 0.55	38.60	39.45	39.10	39.05 ± 0.43
TiO ₂	0.95	0.99	0.98	0.97 ± 0.03	0.96	0.99	0.98	0.97 ± 0.01
Al ₂ O ₃	10.20	11.90	12.00	11.37 ± 1.01	10.80	11.30	11.30	11.13 ± 0.29
FeO	3.20	3.40	3.50	3.37 ± 0.15	3.40	3.20	3.40	3.33 ± 0.12
Fe ₂ O ₃	3.84	4.34	4.24	4.14 ± 0.26	4.47	4.29	4.29	4.35 ± 0.11
Fe ₂ O ₃ T	6.72	7.40	7.39	7.17 ± 0.39	7.53	7.17	7.35	7.35 ± 0.18
MnO	0.13	0.14	0.14	0.14 ± 0.00	0.15	0.15	0.15	0.15 ± 0.00
MgO	11.30	10.80	11.00	11.03 ± 0.25	11.40	10.85	10.90	11.05 ± 0.30
CaO	16.70	15.40	15.10	15.73 ± 0.85	15.30	16.05	15.20	15.52 ± 0.46
Na ₂ O	1.71	1.86	1.95	1.84 ± 0.12	0.83	1.54	1.31	1.23 ± 0.36
K ₂ O	2.04	2.36	2.31	2.24 ± 0.17	2.44	2.41	2.43	2.43 ± 0.02
P_2O_5	1.24	1.16	1.15	1.18 ± 0.05	1.21	1.22	1.20	1.21 ± 0.01
Cr ₂ O ₃	0.12	0.10	0.10	0.11 ± 0.01	0.09	0.09	0.09	0.09 ± 0.00
H_2O^+	3.40	2.90	3.20	3.17 ± 0.25	2.00	2.30	2.50	2.27 ± 0.25
H_2O^-	0.30	0.40	0.40	0.37 ± 0.06	1.30	0.65	0.80	0.92 ± 0.34
CO ₂	4.60	3.95	3.48	4.01 ± 0.56	4.70	4.75	4.45	4.63 ± 0.16
F (ppm)	2190	2310	2180	2227 ± 72	2320	2285	2400	2335 ± 59
LOI	7.45	6.80	6.65	6.97 ± 0.43	8.50	7.48	7.55	7.84 ± 0.57
TOTAL	97.35	98.61	98.57	98.18	97.81	98.68	97.55	98.01
v	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Cr	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Со	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ni	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Rb	69	88	88	82 ± 11	61	76	75	71 ± 8
Sr	1730	1620	1710	1687 ± 49	1410	1825	1910	1715 ± 268
Y	24	28	24	25 ± 2	26	23	26	25 ± 2
Zr	284	281	293	286 ± 6	277	303	307	296 ± 16
Nb	68	75	78	74 ± 5	78	80	90	83 ± 7
Ba	3330	3440	3430	3400 ± 61	3140	3240	3230	3203 ± 55
La	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ce	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Nd	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Pb	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Th	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
U	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
mg = Mg/(Mg + Fe _{total})	0.86	0.85	0.85	0.85 ± 0.0	0.86	0.86	0.85	0.86 ± 0.00
K/(K + Na)	0.44	0.46	0.44	0.45 ± 0.01	0.66	0.51	0.55	0.57 ± 0.08
K ₂ O/Na ₂ O (molar)	0.79	0.84	0.78	0.80 ± 0.03	1.93	1.03	1.22	1.39 ± 0.47

Table 5.1: (Chemical analyses of Middle Mine and English Mine samples, done by XRAL) continued.

	MM1	MM2	MM3	EM1	EM2	EM3
quartz	0.00	0.00	0.00	0.73	0.00	0.00
orthoclase	0.00	0.00	0.00	0.00	0.00	0.00
albite	13.15	14.44	14.65	7.57	12.82	11.43
anorthite	18.32	22.13	21.30	27.75	23.54	25.74
nepheline	0.00	0.00	0.00	0.00	0.00	0.00
leucite	0.00	0.00	0.00	0.00	0.00	0.00
wollastonite	0.00	0.00	0.00	0.00	0.00	0.00
diopside	23.91	19.60	20.11	17.24	19.74	18.02
hypersthene	1.62	3.96	0.53	23.91	11.73	17.58
olivine	23.52	21.33	26.30	0.00	11.15	5.72
acmite	0.00	0.00	0.00	0.00	0.00	0.00
corundum	0.00	0.00	0.00	0.00	0.00	0.00
ilmenite	1.64	1.72	1.65	1.97	1.85	1.92
magnetite	5.06	5.77	5.46	6.99	6.12	6.42
hematite	0.00	0.00	0.00	0.00	0.00	0.00
apatite	0.02	0.02	0.02	0.03	0.03	0.03
chromite	0.16	0.14	0.13	0.14	0.13	0.14
calcite	9.51	8.24	7.03	11.52	10.63	10.44
pyrite	0.00	0.00	0.00	0.00	0.00	0.00
H ₂ O total	3.09	2.66	2.84	2.16	2.26	2.58

Table 5.2: Norm of Middle Mine and English Mine samples, based on the XRAL analyses.

5.3 Geochemical Classification

The discrimination diagrams between the five lamprophyre branches in Rock (1991) were used to verify the classification of the rock. Three simple diagrams were used: CaO *versus* MgO, K₂O/Al₂O₃ *versus* Fe_2O_3/SiO_2 , and V/Cr *versus* Nb/Pb. On the CaO *versus* MgO graph (Figure 5.1) the Yogo analyses fall in the field for ultramatic lamprophyres, which is what was expected. On the K₂O/Al₂O₃ *versus* Fe_2O_3/SiO_2 graph (Figure 5.2), the Yogo analyses fall inside the calc-alkaline field and inside the lamproite field for the graph of V/Cr *versus* Nb/Pb (Figure 5.3). The rock is not ultrapotassic (K₂O/Na₂O > 5), which is one of the characteristics of lamproites, so this last classification can be eliminated. According to Rock (1991), the best possible discrimination diagram is obtain via multigroup linear discriminant analysis (MDA). In this graph, two discriminant functions are plotted against each other. The functions are calculated by applying weights (obtained through MDA) to the wt.% oxide data. The diagram was tested by using average rock analyses for the different branches and weights given in Rock (1991). However, the discriminants calculated for the average branches fell outside the graph and this discrimination diagram had to be abandoned. Thus, the diagrams proposed by Rock (1991) were of no help in the classification of the Yogo dike. In fact, they show that the Yogo dike has a complex geochemistry with similarities to more than one type of lamprophyre.

The analyses of the Yogo dike were then compared to the chemical screens proposed by Rock (1987) for the AL, CAL, UML and LL branches, given in Appendix C. Except for silica, the major elements fall in the range given for ultramafic lamprophyres, and inside the range for alkaline lamprophyres for all oxides except MgO and CaO, which are only 1 or 2 wt.% greater than the upper limit. Whole rock K/(K + Na) ratios vary between 0.42 to 0.69, which fit the ultramafic lamprophyre range, as well as the *mg* (100Mg/Mg + Fe_{total}) number values of 85 and 86 which are inside the range given by Rock (1987) of 78.1



Figure 5.1: Simple discrimination between the five lamprophyre branches using CaO vs. MgO. Analyses were recalculated to 100% without MnO, H₂O, and CO₂ prior to plotting. Analyses from Carleton were not plotted because they are incomplete. Diagram modified from Rock (1991). UML: ultramafic lamprophyres; AL: alkaline lamprophyres; CAL: calc-alkaline lamprophyre; LL: lamproites.



Figure 5.2: Simple discrimination between the five lamprophyre branches using ratios of major oxides. Analyses were recalculated to 100% without MnO, H₂O, and CO₂ prior to plotting. Diagram modified from Rock (1991).



Figure 5.3: Simple discrimination between the five lamprophyre branches using trace element ratios. Diagram modified from Rock (1991).

 \pm 8.5. Alkaline lamprophyres have *mg* numbers averaging 64.5 \pm 9.6, which is low in comparison with the value for the Yogo dike. The Yogo dike chemistry indicates that the rock is, except for silica, inside the ultramafic lamprophyre compositional screen.

5.4 Mineralogical Classification

As proper classification of the rock can not be achieved with certitude using geochemical analyses alone (which is usually the case for this type of rock), mineralogy and mineral chemistry were compared to the respective screens given by Rock (1977, 1984, 1986, 1987). The rock is free of feldspar which eliminates the CAL classification totally (Appendix C), as well as varietal names camptonite and sannaite of the alkaline lamprophyres (Appendix C), leaving only monchiquite. The rock contains no mellite, which eliminates the UML types alnoite and polzenite (Appendix C). The *mg* number of the rock (85 to 86) indicates an ultramafic composition. The *mg* number for clinopyroxene cores (see Section 6.1) varies between 82 and 98. This is closer to the ultramafic range for clinopyroxene of 80.2 ± 10.0 than to the values of 71.5 ± 15.6 for alkaline lamprophyres. Similarly, the *mg* number for phlogopite ranges from 80 to 90 which is inside the range for phlogopites of ultramafic lamprophyres. In summary, considering the geochemistry and the mineralogy of the Yogo dike, it can be classified either as an aillikite (UML), a damkjernite (UML), or an ouachitite (UML). In conclusion, the Yogo dike was classified as an ultramafic lamprophyre (Rock 1987, 1991; Meyer and Mitchell, 1988) and new data confirm this classification.

To determine what type of ultramafic lamprophyre the Yogo dike really is, the analyses were compared to Rock's (1991) average ouachitite, damkjernite and aillikite analyses (Table 5.3) and the following differences appear. The SiO₂, Al₂O₃, and CaO contents of the Yogo dike are higher than those of the

	Yogo Dike Average	Yogo Dike Average (XRAL)	Average Ouachitite	Average Damkjernite	Average Aillikite
	(Carleton)				
Samples	6	6	36	45	232
SiO ₂	39.64-40.43	38.80-39.80	36.50	35.00	29.50
Al_2O_3	10.62-12.53	10.20-12.00	9.10	7.20	5.40
Fe_2O_3	6.79-7.55	6.72-7.53	13.20	13.60	14.80
MgO	11.04-11.85	10.80-11.40	11.40	12.00	15.90
CaO	16.62-18.40	15.40-16.70	13.40	13.30	13.50
Na ₂ O	0.73-2.02	0.83-1.95	1.70	1.60	0.45
K ₂ O	2.10-2.45	2.04-2.44	2.10	2.20	1.60
TiO ₂	1.00-1.04	0.95-0.99	2.80	3.70	3.40
P_2O_5	1.14-1.23	1.15-1.24	1.10	1.10	0.82
MnO	0.13-0.15	0.13-0.15	0.19	0.20	0.25
H_2O		2.00-3.40	3.20	3.60	3.80
CO ₂		3.48-4.75	4.50	6.00 (19)	10.50 (137)
S			0.22 (9)		0.20 (40)
V	141-156		235 (10)	265 (26)	270 (98)
Cr	731-973	0.09-0.12ª	263 (10)	600 (22)	450 (132)
Co	32-45			77 (5)	90 (23)
Ni	20-230		300 (10)	280 (25)	450 (132)
Zn	68-104		146 (10)	120 (26)	105 (132)
Rb	62-98	61-88	55 (11)	75 (26)	60 (139)
Sr	1428-1950	1410-1910	1300 (11)	1300 (26)	950 (147)
Y	16-18	23-28	33 (10)	46 (26)	25 (99)
Zr	198-215	277-307	350 (11)	465 (26)	315 (127)
Nb	64-83	68-90	117 (11)	130 (26)	100 (139)
Ba	3559-4081	3140-3440	950 (11)	1100 (26)	1180 (132)
La	139-201		106 (9)	86 (9)	140 (38)
Ce	294-458	•	220 (9)	160 (9)	270 (45)
Nd	119-171		66 (6)		104 (26)
Pb	24-35		8 (9)	11 (5)	7 (43)
Th	11-14		14 (9)	11 (21)	8 (88)
U	10-12		3 (8)	16 (5)	4 (33)

Table 5.3: Yogo dike average chemistry compared to the average chemistry for ouachitite, damkjernite and aillikite (Rock, 1991). Numbers in brackets refer to the number of analyses. Oxides are in wt.%, traces are in ppm, except where specified.

*Wt.%

average ouachitite, while TiO_2 and Fe_2O_3 are significantly lower (~1 wt.% compared to 2.8 wt.%, and 7 wt.% compared to 13 wt.%, respectively). MgO, Na₂O, K₂O, P₂O₅, and MnO are close to the average ouachitite. Trace elements Cr, Ba, Pb, U are significantly (by a factor of three) higher than the average ouachitite, while La, Ce, Nd, Rb, Sr are slightly higher and V, Ni, Zn, Y, Zr and Nb are slightly lower.

The Yogo dike chemistry shows about the same dissimilarities with the average damkjernite, except that the contrast is even greater (the damkjernites are poorer in SiO_2 , Al_2O_3 and richer in TiO_2 and Fe_2O_3 than the ouachitites). The Yogo dike shows very few similarities with the average aillikite, as can be seen in Table 5.3. Thus, the Yogo dike can be classified either as a ouachitite or a damkjernite, but is closer to the former.

5.5 Petrogenetic Relationships Between the Yogo Dike and the Yogo Peak Intrusion

5.5.1 Introduction

The origin of the Yogo dike intrusion is unknown. Pirsson (1900) proposed a link between the Yogo dike and the Yogo Peak intrusion. The Pearce Element Ratio (PER) method was used to test this hypothesis using data from Embry's (1988) petrographical, geochemical and petrological study of Yogo Peak, and chemical analyses acquired during the present study of the Yogo dike.

Embry (1988), describes Yogo Peak as a small, elongated intrusion, trending northeast to southwest. It is about 6.5 km long by 0.5 to 1.8 km wide. The stock is composed of shonkinite at the ends grading into mafic monzonite, monzonite, syenite and granite towards the centre. Embry (1988), notes a gradational and irregular contact between the rock types, without chilled margins. The different rock types have the same mineralogy with a different percentage of the common minerals. An interesting feature of this intrusion is that it is composed of both alkaline and calc-alkaline rocks. Embry proposed a magma mixing event to explain this feature and some field relationships such as xenoliths of shonkinite in the syenite, diffuse syenite bands in the shonkinite, and disequilibrium textures such as the presence of both olivine and quartz in some of the monzonites and syenites.

5.5.2 Theory of the Pearce Element Ratio Method

The Pearce element ratio (PER) method is a relatively new technique that overcomes the problem of closure resulting from normalization of oxide totals to 100%. Pearce element ratio diagrams (composed of two Pearce element ratios or two linear combinations of Pearce element ratios) use molar ratios as axes. By definition, PER is a ratio of 2 concentrations of constituents (elements) in a system (rock) which are expressed in a molar context; the denominator constituent did not participate in any material transfer process which has affected the rock. By using moles instead of mass concentrations in PER analysis, the resulting material transfers can be related directly to mineral formulae and chemical reactions. This allows solid-solution mineral composition variations to be accommodated by simple addition of PER's. Most importantly, these features allow development of linear compositional variation (fractionation) models that can represent the geochemical heterogeneity that may be present in rocks before the advent of metasomatism associated with mineralization (Stanley and Madeisky, 1993).

PER analysis can only proceed when three basic conditions (assumptions) are met: (1) the rocks under investigation are related to a common parent that at one time was homogeneous; (2) at least one material transfer process has acted to create the geochemical variability observed in the rocks; and (3) at least one

constituent (element) in the rocks did not participate in (was conserved during) the material transfer process(es).

It is important to understand the terminology commonly used with PER analysis. An immobile element is an element that is neither significantly added nor removed from a rock during metasomatism because of its low solubility in aqueous fluids (Stanley and Madeisky, 1993). Potential candidates include Zr, Ti, Al, Nb, Y, Th, Hf, and others. An incompatible element is one that does not occur significantly in mineral or volatile phases that crystallize, evolve or dissolve from/into a melt and which is subsequently physically redistributed within (crystal or volatile sorting) or removed (fractionation) from the melt by other processes. Examples are Zr, Nb, Y, Th, Ti, P, K, V, and others. A conserved constituent is an element that does not participate in any material transfer process that has affected the system. A conserved element is both immobile and incompatible (Stanley and Madeisky, 1993).

5.5.3 Sources of Lithogeochemical Variability

One or many of the following explanations are ususally responsible for variability in a series of analyses: (1) measurement error, i.e. sampling or analytical error; (2) closure, which may be responsible for most of the variations observed in a set of rock compositions; (3) fractionation crystal sorting; (4) compositional mixing; and (5) metasomatism.

5.5.4 Is the Yogo Dike Genetically Related to the Yogo Peak Intrusion?

Two types of diagrams can be used to answer this question: (1) conserved constituent scatterplots where two conserved elements are plotted against each other, and (2) PER conserved constituent diagrams where ratios of two conserved elements are plotted against each other (the denominator element being common to both ratios). If the data all plot at a single point on the diagram, the three consitutents are equal and the rocks are cogenetic. Conserved constituent scatterplots are usually the first step of a PER analysis. When these simple diagrams are very conclusive, PER diagram do not need to be plotted. Both of these diagrams rely on the fact that conserved constituent ratios of rocks related to a common parent which was at one time homogeneous with respect to those conserved constituents will be equal (Stanley and Madeisky, 1993).

On the conserved constituent scatterplots if the data plot along a line, given measurement error, which passes through the origin, the samples have the same conserved element ratio. Similarly, on a PER conserved constituent diagram, if the data plot at a single point, given measurement error, the samples have equal conserved element ratios on both axes. If the data plot along a horizontal or vertical line, then only one of the ratios is constant (the ordinate or abscissa, respectively).

When the data plot on a straight line that does not pass through the origin, the rocks are either (1) cogenetic, or (2) derived from at least two parents with initial compositions and material transfers that coincidentally produce a linear relationship (compositional mixing) on the conserved constituent scatterplot.

To test the cogenetic hypothesis between the rocks of the dike and the Yogo Peak intrusion, conserved constituent scatterplots were computed for the different major oxides and trace elements suspected to be conserved elements (Zr, Nb, Y, P_2O_5 , Ti O_2 , Al₂O₃ and K₂O). The following graphs were plotted (Table 5.4).

Table 5.4: Conserved constituent scatterplots

x	У	x	у	x	у
Nb	Y	Zr	Y	K ₂ O	Al_2O_3
Nb	K ₂ O	Zr	Nb	K ₂ O	Y
Nb	Al_2O_3	Zr	TiO ₂	P_2O_5	TiO ₂
Nb	P_2O_5	Zr	K ₂ O	P_2O_5	K ₂ O
Nb	TiO₂	Zr	Al_2O_3	P_2O_5	Y
Nb	Ba	Zr	P_2O_5	TiO ₂	Y
		Al_2O_3	P_2O_5	Al ₂ O ₃	K ₂ O
Cogenetic rocks will lie on a straight line passing through the origin. A few of these graphs are presented in the following figures (5.4 to 5.6). The other graphs also show very clearly the difference in chemistry between the rocks of the Yogo Peak intrusion and the Yogo dike. Two main conclusion can be draw from the graphs: (1) the data from the Yogo Peak intrusion do not plot on a single line; therefore they do not represent a cogenetic magmatic suite, and (2) the Yogo dike samples plot away from the Yogo Peak samples meaning that they are chemically distinct. Embry (1988) suggested that magma mixing of a mafic shoshonitic suite and a granitic suite was responsible for Yogo Peak. The graph presented here confirms that Yogo Peak is derived from more than a single magmatic suite. The first two point listed in Section 5.5.3 (e.g. measurment error and closure) can not explain the high variability between the Yogo Peak samples and the Yogo dike samples. Fractionation (point 3 of section 5.5.3) is also rejected on the basis that Nb is more abundant in the more primitive intrusion (Yogo dike) than in the more evolved one (Yogo Peak). Since Nb is an incompatible clement it should be more concentrated in the most evolved rock if they are both cogenetic. It is not possible to reject the fourth point (magma mixing or assimilation) based on this analysis only. In summary, the variability seen on the diagrams can be due to the fact that the intrusions are not related or that one or both had assimilated some material before crystallization.



Figure 5.4: Conserved constituent scatterplot of Y vs. Nb for samples from the Yogo Peak intrusion and samples from the Yogo dike. The circles represente shonkinite and mafic monzonite; the squares and stars represente monzonite, syenite, quartz-bearing alkali syenite granite and rhyolite. The subdivision between the three suites of samples from Yogo Peak is based on rock types and linear trends formed by the samples on conserved constituent scatterplots (Table 5.4).



Figure 5.5: Conserved constituent scatterplot of $Al_2O_3 vs$. Nb for samples from the Yogo Peak intrusion and samples from the Yogo dike. For description of the symbols see Figure 5.4.



Figure 5.6: Conserved constituent scatterplot of Zr vs. Nb for samples from the Yogo Peak intrusion and samples from the Yogo dike. For description of the symbols see Figure 5.4.

6. MINERAL CHEMISTRY

6.1 Pyroxene Chemistry

The only pyroxene present in the Yogo ouachitite is clinopyroxene. The two clinopyroxene populations (megacrysts and micro-phenocrysts) were analyzed using a CAMECA electron micoprobe. Operating conditions and standards used for the analyses are given in Appendix F.

As noted previously in Chapter 3.1, all the pyroxenes are zoned. The differences in composition between megacrysts and micro-phenocrysts are not as marked as the differences in composition between the rims of a single pyroxene. For this reason, megacrysts and micro-phenocrysts will be described together. Typically, cores are diopsidic or augitic (Mg and Ca-rich, close to the diopside field), with outside rims progressively richer in Al₂O₃, Fe₂O₃, and TiO₂ and poorer in MgO, and SiO₂. Analyses are presented in Appendix E, which also includes structural formulae where iron is calculated as Fe²⁺ or Fe³⁺ based on charge balance and stoichiometry. Cation distribution over tetrahedral and octahedral sites was done according to Morimoto (1988). Names were also given according to Morimoto's (1988) classification scheme. The table includes the composition of the pyroxenes in term of their end-members (NaFeSi₂O₆ (amite), NaAlSi₂O₆ (gadeite), CaTiAlAlO₆ (TiCaTs), CaFeAlSiO₆ (FeCaTs), CaCrAlSiO₆ (CrCaTs), CaAlAlSiO₆ (AlCaTs), Ca₂Si₂O₆, Mg₂Si₂O₆, Fe₂Si₂O₆), calculated according to Lindsley (1983) with addition of the Ti-Tschermack component (CaTiAlAlO₆). The proportion of the FeCaTs component (CaFeAlSiO₆) in which Fe is present as Fe³⁺, is highly sensitive to the quality of the analysis; for analyses with low totals, more Fe₂O₃ is allowed during the calculation with respect to FeO to increase the totals, which increases the amount of the FeCaTs component.

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Yogo pyroxenes are poor in the acmite, jadeite, TiCaTs, and CrCaTs components and relatively rich in the AlCaTs and FeCaTs components. The megacrysts have up to 14.5% of the AlCaTs component (analysis G7-2), and up to 18.6% for pyroxene from a pyroxene-pleonaste xenolith (analysis G10-9).

As mentioned previously, cores are diopsidic or augitic (Mg and Ca-rich), with rims progressively richer in Al_2O_3 , Fe_2O_3 , TiO_2 , and poorer in MgO, SiO_2 , as represented on the variation diagrams of Al, Ti, Si, *mg* number, Cr plots against Ca/(Ca + Mg) in Figure 6.1. The most primitive pyroxene analyzed (33A3-3 to 5) has an *mg* number of 98. Its core is almost pure diopside and its rim has a composition similar to the core of most of the megacrysts. This pyroxene is Al, Fe, Na, Ti, Cr-poor diopside with the formulae: $(Ca_{0.98}Na_{0.02})(Mg_{0.98-0.99}Fe^{3+}_{0.02})(Si_{1.98-1.99}Al_{0.01-0.02})_2O_6$. Relatively pure diopsides occur in some thermally metamorphosed siliceous dolomites and in skarns (Deer el al., 1980).

Pyroxene microphenocrysts have a range of compositions that is equivalent to the rims of the megacrysts. Mg numbers for the megacrysts range between 84 and 91. One megacryst core has an mg number and composition more evolved than its rim (megacryst G7) meaning that this megacryst is a xenocryst. Pyroxenes from a pyroxene-phlogopite glomerocryst (G2) are primitive in composition with an mg number of 88 to 89, a low Al content (~3% wt.% Al₂O₃), and a high Mg content (~17.5 wt.% MgO). They are magnesian calcian aluminian chromian augite. One of the megacrysts analyzed (G4) is slightly more primitive than the pyroxenes from pyroxene-phlogopite glomerocrysts. It has an mg number that varies between 90 and 92, is low in Al (1.76 to 2.50 wt.% Al₂O₃), high in Mg (17.37 to 18.22 wt.% MgO), and is Cr-bearing (0.78 to 1.21 wt.% Cr₂O₃). In term of nomenclature, it is either a magnesian-calcian-chromian augite or an aluminian-chromian diopside (Appendix E).



Figure 6.1: Variation diagrams for pyroxenes.



Figure 6.1: (Variation diagrams for pyroxenes) continued.

Some of the clinopyroxene cores or, sometimes, some of the rims between the core and the outside rims, are chromium rich, with up to 1.65 wt.% Cr_2O_3 . Typically, rims or cores that have a high *mg* number (~90) are usually Cr-rich (often more than 1 wt.% Cr_2O_3). The outside rim is never chromium-rich.

Outside rims are typically Al rich, with up to 11 wt.% Al_2O_3 . Due to their high Al-content, they often are Si deficient. In term of composition, they are subsilicic aluminian ferrian diopside. Pyroxenes from a pyroxene-pleonaste xenolith have a similar composition. The formulae of these pyroxenes is: $(Ca_{0.93-0.98} Na_{0.02-0.05}Fe^{2+}_{0.00-0.08})(Mg_{0.64-0.73}Fe^{3+}_{0.14-0.22}Ti_{0.03-0.07}Al^{VI}_{0.07-0.19})(Si_{1.62-1.75}Al^{IV}_{0.25-0.38})O_6.$

The pyroxenes are Na-poor (<1 wt% Na₂O), except for 1 grain which has a slightly higher Na₂O content (2 wt.% Na₂O) in its core. The rim of this grain has a Na₂O content of about 1 wt.%.

Pyroxene compositions are plotted on the Ca-Mg-Fe ternary diagram on Figure 6.2. Pyroxenes plot in the diopside and augite fields of Morimotto (1988) and the diopside, salite, endiopside and augite field according to the older classification of Deer *et al.* (1980).

In the traditional method of plotting quadrilateral pyroxenes in terms of Ca + Mg + Fe = 100%, any nonquadrilateral component causes substitution of R^{3+} ions for Mg and Fe in the M1 site. This in turn causes the ration Ca/Ca + Mg + Fe to increase, and in some cases to show CaSiO₃ content greater than 50%. Pyroxenes rich in the Ca-Tschermack, Ti-Tschermack and Cr-Tschermack molecules (CaAlAlSiO₆, CaTiAl₂O₆, CaCrAlSiO₆, respectively) are not well represented on this diagram and could project on another field. Pyroxene rims are Al-rich (up to 11 wt% Al₂O₃), Mg-poor compared to the cores and often plot higher than the diopside field or to the left of the pyroxene cores on the diagram (Ca,Mg-rich). A better representation of these pyroxenes would be given on a Ca-Mg-Fe-Al quadrilateral.

PYROXENES





Pyroxenes rich in the CaTs component (CaAlAlSiO₆) crystallize at high temperature (Deer el al., 1980, Robinson, 1981). Yogo pyroxenes seem to follow an opposite trend; the rims are richer in the CaTs component than the cores. This is in contradiction with the observations that the Ts molecule increases with increasing lithostatic pressure. However, according to Deer et al. (1980) augite crystallizing near the liquidus shows an increase in the Ca-Tschermak's (CaAl₂SiO₆) and jadeitic (NaAlSi₂O₆) component and a decrease in the ferrosilite ($Fe_2Si_2O_6$) component with increasing pressure. This could be the explanation for the observation that augites of alkali basalts usually have rims richer in Al than their cores. Barberi et al. (1971) suggested that the alkaline series may be due to crystallization and differentiation under conditions of high magmatic water pressure rather than high lithostatic pressure. Precipitation of pyroxene takes place before plagioclase with the consequence that the pyroxene is enriched in the CaAl₂SiO₆ component, and has high titanium content due to the replacement $R^{2+} + 2Si \Leftrightarrow Ti^{4+} + 2Al$. At lower water pressures plagioclase crystallizes before pyroxene, leading to a smaller $CaAl_2SiO_6$ content and less titanium, thus enabling iron enrichment and the pyroxene trend is more tholeiitic in character. A sympathetic relationship between titanium and aluminium is, however, not universal, and Gramse (1970; in Deer el al., 1980) has described phenocrystal augites from the Nordhessen and Sudniedersachen basalts, the cores of which are richer in the CaAl₂SiO₆ component and have a smaller titanium content in the outer zones of the crystals as well as in the pyroxenes of the groundmass.

Pyroxenes with similar behaviour are found in the clinopyroxenite and spinel pyroxenite nodules of the Ladinian volcanic rocks, Predazzo-Monzoni complex, northern Italy (Deer *et al.*, 1980). The diopsides of the clinopyroxenites have low Al contents (1.26 to 2.36 wt.% Al₂O₃) in contrast to those of the associated augite megacrysts (13.8 wt.% Al₂O₃). The nodules are interpreted as cognate xenoliths derived by crystal

settling from an alkali-basalt magma at 15 to 25 km in the crust, whereas the megacrysts crystallized from the same magma at the crust-mantle boundary or in the upper mantle.

6.2 Spinels

Green spinel is an conscipicious accessory mineral in the Yogo ouachitite. Corundum and spinel $(MgAl_2O_4)$ are two minerals often present together in metamorphic rocks. The unusual occurrence of pleonaste in the ouachitite was studied during the course of this project because of the association corundum-spinel, hoping that it would help to understand the presence of sapphire in the Yogo dike.

The four types of pleonaste spinel described in Chapter 3.7.2, together with the groundmass spinel, magnetite, were analyzed using the same equipment described in Chapter 6.1. Experimental conditions are given in Appendix F. Analyses of the spinels are given in Appendix E. The analyses are also presented graphically on the simplified spinel diagram shown as Figure 6.3.

6.2.1 Magnetite

The core of groundmass magnetite is often a mixture of magnetite and quartz which, together with the small size of the grains, create analytical problemss such as low totals and analyses rich in SiO₂. Only analyses with resonable totals (~97%) were plotted on the graph. Magnetite plots on the upper right corner of the graph $Fe^{3+}/(Fe^{3+} + Al + Cr)$ versus $Fe^{2+}/(Fe^{2+} + Mg)$. Groundmass magnetite is Al-rich, containing up to ~8.5 wt.% Al₂O₃, Ti-poor, usually with less than 2 wt.% TiO₂, except for one analysis with 5 wt.% TiO₂. Some grains are zoned. The rim is Al,Ti-enriched compared to the core. Mn content varies between 0.5 to 2.8 wt.%. Some grains contain a significant among of MgO (up to 2.8 wt.% MgO). Mg-rich grains are also Al-rich suggesting that the magnetite is enriched in the spinel (MgAl₂O₄) component. Groundmass



Fe ** /(Fe*+AI +Cr)

Figure 6.3: Composition of Yogo spinels.

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magnetite is usually Cr-poor (with less than 0.5 wt.% Cr_2O_3), except for one grain (31i-2-1) with 15.74 wt.% Cr_2O_3 . This grain is also Al-rich (12.57 wt.% Al_2O_3).

The groundmass magnetite from the Yogo dike is similar in composition to magnetite found in carbonatite intrusions such as the Jacupiranga complex in Brazil (Gaspar and Wyllie, 1983), except for the higher Alcontent of magnetite from the Yogo dike.

Magnetite rimming pleonaste spinel is usually richer in Al than groundmass magnetite, although some of the analyses are similar to those of groundmass magnetite. The problem of magnetite intermixed with quartz encountered with groundmass magnetite was accentuated here. Only a few analyses with totals close to 100% were obtained. These analyses (25a5-4, 31i-5-1, 31i-2-5, 31i-2-7) indicate a high Al and Mg content (up to 14.14 wt.% Al₂O₃ and 5.78 wt.% MgO). Magnetite rimming pleonaste spinel on sapphire (the last two analyses listed previously) are the most Al-enriched. This magnetite is Al-rich (Al₂O₃ between 12 and 14 wt.%), Mg-rich (MgO between 4 and 6 wt.%), Cr-enriched (Cr₂O₃ up to 0.5 wt.%), and slightly Ni-enriched compared to the groundmass magnetite.

6.2.2 Pleonaste Spinel

The four types of pleonaste spinel (as grains associated with phlogopite, as grains associated with clinopyroxenes from xenoliths, as discrete grains in the matrix, and as rims around the sapphires) all plot in the same area of Figure 6.3. The $Fe^{2+}/(Fe^{2+} + Mg)$ ratio (or hercynite, $FeAl_2O_4$ component) varies from 0.16 to 0.38. Pleonaste is the name given to spinels forming a solid solution between the spinel solid solution (MgAl₂O₄) and hercynite (FeAl₂O₄). The Fe³⁺ component (recalculated by fixing the number of cations at 32 and the number of anions at 24) is less than 0.05 per unit formulae in the pleonaste spinel analyzed.

The pleonaste grains in matrix are the most Mg-rich while the pleonaste as inclusions in phlogopite are the most Fe-rich. The pleonaste in matrix are also the only ones that are Cr-bearing (up to $0.87 \text{ Cr}_2\text{O}_3$). Pleonaste on phlogopite are usually slightly higher in TiO₂ and ZnO. The *mg* number of the pleonaste spinels (Mg/(Mg + Fe), given in Appendix E with the analyses, varies between 63 and 84. The *mg* number of associated pleonaste and pyroxenes are, respectively, 71 to 76 and 84 to 91. The pleonaste rims on sapphire have an *mg* number varying between 73 and 77, which is lower than the whole rock *mg* number (84 to 86). Pleonaste found in the groundmass have an *mg* number between 75 and 84. These spinels are often zoned, showing a thin rim lighter in colour on a BSE microphotograph. These rims have a significantly higher FeAl₂O₄ end-member component.

Brearley (1987) studied the pyrometamorphic breakdown of Fe-Al biotite into Mg-Al biotite + magnetite + hercynite spinel + K-feldspar/melt + vapour. His experiments were conducted between 800 and 850°C. He observed that an increase in the *mg* number of biotite produces an increase in the *mg* number of the spinel product and that an increase in temperature of reaction also produces a spinel with a higher *mg* number. Other experiments by Brearley and Rubie (1990) demonstrated that in the presence of H_2O muscovite breakdown reactions are delayed. Grapes (1986) also described the occurrence of green spinel (pleonaste) as decomposition products of biotite.

6.2.3 Conclusion

It is interesting to note the similarities in composition for these different types of spinels. The composition of the spinel rimming sapphires reflects the composition of the magma at the time of incorporation of the sapphires into the magma (if the xenocryst hypothesis is valid) or the time of rapid changes in pressure and temperature conditions necessary for a phenocryst to be resorbed.

Four hypotheses have been explored by Wagner et al. (1987) to explain the presence of Al-rich spinel (pleonaste) as inclusions in phlogopite or leucite of the West Kimberley lamproites, which are Al-deficient: (1) aluminous spinel as early precipitates, (2) aluminous spinels as exsolved phases, (3) aluminous spinels as xenocrysts, and (4) aluminous spinel as products of the destabilization of pre-existing aluminous phases. The first hypothesis is rejected on the basis that early precipitate spinels are Cr-rich and Al-poor compared to the Al-rich and Cr-poor (usually < 0.5 wt.%) pleonaste spinel. It is also hard to understand how an Alrich mineral would be the first to crystallize from an non-corundum normative magma. Wagner et al. (1987) rejected the second hypothesis on the basis that peraluminous minerals are rarely found in Aldeficient liquids. The large proportion of spinel with respect to phlogopite host also tends to exclude this hypothesis. The third hypothesis is easily rejected on the basis of the present study. It would be hard to justify how four different type of spinel occurrences would have a very similar composition, which is the most striking feature of the pleonaste spinels observed. Although pleonaste spinel has been observed associated with phlogopite and pyroxenes in different studies, it has never been observed both associated with pyroxene and phlogopite in the same rock. The fourth hypothesis was found to be the most probable by Wagner et al. (1987), based on the experiments of Grapes (1986) and Brearley (1987) on the breakdown of muscovite and biotite at high temperature. Wagner et al. (1987) concluded that the pleonaste spinels were the products of pre-existing trioctahedral micas incorporated within the lamproite magma.

As previously stated in the section on petrography, phlogopite grains hosting pleonaste spinel are often pale in colour, which suggests a high Mg content. It is not possible to differentiate them in terms of colour and morphology from phlogopites that do not host spinel. Unfortuantely, pleonaste-bearing phlogopite megacrysts have not being analyzed during this project, due to time constraints. It would be interesting to see if these are Al-enriched compared to the other megacrysts. These phlogopite megacrysts are seen as cumulate phases crystallized around the magma chamber. It is uncertain why some of the megacrysts have pleonaste inclusions and some do not. The author thinks that the pleonaste is the result of destabilization of an Al-rich phase. The similar composition of the spinels is probably due to the fact that pyroxenes, phlogopite and the whole rock have similar *mg* numbers. Some of the pleonaste-bearing megacrysts or xenoliths are definitely xenocrystic and could have some relation with the sapphires, but some of the megacrysts (phlogopite megacrysts) look as though they are cognate to the magma.

6.3 Phlogopite

Chemical compositions of phlogopites were obtained with a CAMECA electron microprobe. An acceleration voltage of 15 kV and a current of 2 nA were used. The standards used were albite for Na and Si, phlogopite for Fe and Ti, diopside for Mg and Ca, chromite for Cr, spessartine for Mn, barite for Ba, and fluorite for F. Counting times were 20 seconds. Structural formulae were computed (using the program FORMULA) on 22 anions. Iron was assume to be Fe^{2+} . Analyses are presented in Appendix E.

The composition of the micas from the Yogo dike varies greatly from core to rim. However, both cores and rims are classified as phlogopite. They are not pure phlogopite end-member but they are solid solutions between phlogopite ($K_2Mg_6Al_2Si_6O_{20}(OH)_4$), annite ($K_2Fe^{2+}_6Al_2Si_6O_{20}(OH)_4$), eastonite ($K_2Mg_5Al_4Si_5O_{20}(OH)_4$), and fluorphlogopite ($K_2Mg_6Al_2Si_6O_{20}(F)_4$). Chemical variations between cores and rims are represented on Figure 6.4.

The most primitive phlogopite is chromium-rich (0.5 to 1.0 wt.% Cr_2O_3), Mg-rich (20 to 22 wt.% MgO), and has an *mg* number of 95 (Appendix E). The *mg* number of phlogopite megacryst cores varies between 84 and 90, which is the same as most of the pyroxene megacrysts. Phlogopite rims are Ba-rich (up to 6 wt.% BaO), which is a common feature of mica from carbonatites and ultramafic lamprophyres. Analyzing Ba and Ti together is however problematic as both elements have adjacent K α peaks. The



Figure 6.4: Yogo micas plotted on the ternary diagram Al-(Mg+Fe)-Ti. The circles represent megacryst cores, the cross megacryst rims, and the squares phlogopite in matrix.

background for each element should be selected so that the base of the adjacent peak is not included. This was tested before the data was processed. However, the analyses show a very strong correlation between Ba and Ti. However, the possibility of analytical problems should also be pointed out even if care has been taken to avoid them.

The cation totals in the tetrahedral site range from Si = 5.00 to 5.50 and Al = 2.50 to 3.00. The octahedral site is partially filled with 5.32 to 5.77 cations out of a total of 6. Mg makes up 3.91 to 4.70 of this, Fe^{2+} between 0.55 and 1.05, Ti between 0.15 and 0.46, Al^{VI} between 0.06 and 0.27, Cr between 0 and 0.12, and Mn less than 0.02. The interlayer comprises K, Ba, Na and some Ca. K ranges from 1.44 to 1.88 (out of 2), Ba from 0.04 to 0.33, Na from 0.08 to 0.18, and Ca less than 0.01 cations per formula unit. F has also been analyzed and fills between 0 and 0.41 of the hydroxyl sites.

The mg number ((Mg/(Mg + Fe) x 100) varies between 79 and 90, the cores having the highest values. Si, Ti, Ba, Al, Fe, and Cr have been plotted against the mg number (Figure 6.5) for the phlogopites in the matrix, megacryst cores, and megacryst rims. Si increases slightly as the mg number increases or as the mica becomes more phlogopitic. Ti, Ba, Fe, and Al follow an opposite trend. From mg = 86 to 90, there is a steep increase of Cr in the phlogopite. Theses phlogopite are Cr-rich with up to 1 wt.% chromium oxide. The composition of megacryst rims partially overlaps the composition of the matrix phlogopite.

All the graphs show the presence of two distinct populations: one with *mg* numbers ranging from 79 to 83, and the other with *mg* numbers greater than 86. Only one point falls in the gap between the two groups of data. The gap might be due to the limited number of analyses.



Figure 6.5: Phlogopite variation diagrams. $Mg = Mg/(Mg+Fe_{total})$





The most mafic phlogopite analyzed has the following structural formula:

 $(K_{1.77}Na_{0.13}Ba_{0.06})(Mg_{4.61}Fe^{2+}{}_{0.56}Al^{V_{1}}{}_{0.24}Ti_{0.20}Cr_{0.11})(Si_{5.55}Al_{2.45})O_{20}(OH_{3.78}F_{0.24}).$

The most evolved phlogopite analyzed (PH4D1) has the following formula:

 $(K_{1.53}Na_{0.09}Ba_{0.33})(Mg_{4.06}Fe^{2+}_{1.03}Al^{V_{1}}_{0.08}Ti_{0.46})(Si_{5.02}Al_{2.98})O_{20}(OH_{3.58}F_{0.42}).$

6.4 Ocelli

Two types of ocelli have been recognized; one type composed of zeolites and carbonates with accessory barite and one type with carbonates, analcime and green amphibole. Backscattered imaging on the ocelli revealed that they are zoned. The core is composed of calcite which is rimmed by dolomite and then by analcime. The core often contains barite grains (Figure 3.5).

6.4.1 Carbonates

Analcime has been analyzed using an electron microprobe, and the results are presented in Section 6.4.2 below. A few carbonate analysis have been obtained on the same ocelli, using the same analytical conditions as for analcime (Appendix F). The chemical analyses for the carbonates are not precise because the correct standards were not used, but they do give an idea of the composition of the carbonates from the ocelli. These are presented in Table 6.1. Carbonates from ocelli vary in composition from calcite and dolomite to ankerite.

	1	2	3	3b	5	6	7	8	9
Fe ₂ O ₃	10.93	2.64	1.82	0.79	0.51	0.57	0.58	5.49	4.43
Na ₂ O	0.03	0.03	0.00	0.01	0.00	0.02	0.00	0.84	0.04
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.02
Al ₂ O ₃	0.09	0.00	0.02	0.00	0.01	0.00	0.02	2.91	0.00
MnO	0.38	0.27	0.25	0.10	0.04	0.09	0.07	0.60	0.85
MgO	14.85	18.63	20.87	20.52	20.62	19.77	20.86	15.07	15.32
CaO	28.70	31.07	29.70	30.64	30.40	31.36	30.75	24.68	32.90
SiO ₂	0.00	0.00	0.00	0.02	0.04	0.00	0.00	7.88	0.00
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00
Total	54.98	52.63	52.65	52.09	51.63	51.82	52.28	57.80	53.56
Species	ankerite	dolomite	dolomite	dolomite	dolomite	dolomite	dolomite	ankerite	ankerite

Table 6.1: Analyses of carbonates from ocelli.

6.4.2 Analcime

Analcime Structure and Composition

Analcime (NaAlSi₂O₆·H₂O) is found in the Yogo dike in the matrix and in ocelli. Analcime belongs to the analcime-wairakite series which is one of the seven groups forming the zeolite family. Analcime is isostructural with the species wairakite, pollucite, leucite, viseite and kehoite (Flanigen, 1981). (Si,Al)O₄ tetrahedra form rings of six tetrahedra and rings of four tetrahedra by sharing an oxygen atom in one corner of the tetrahedra. Each corner oxygen is shared by two tetrahedra (Deer *et al.*, 1978) Sixteen large cavities are occupied by water molecules whereas a set of 24 smaller cavities are partially filled by sodium (Deer *et al.*, 1978). According to Tschernich (1992), most analcime crystals are sodium-dominant, but there are some that show a wide range of exchangeable cations (e.g. Na, Ca, Cs and Mg). Substitution of Al for Si necessitates an increase in the (Na + K + Ca) content to maintain charge balance (Deer *et al.*, 1978). Two complete series exist, one between sodium analcime and calcium wairakite, and another between sodium analcime and sodium pollucite. Analcime is defined as the member of these series with greater than 50% Na, regardless of the structure.

Analcime occurs as a primary mineral in some intermediate and basic rocks. It is a low temperature mineral and so will crystallize at a late stage. It can also crystallize from hydrothermal solutions and occurs in vesicules (Deer *et al.*, 1978). The distinction between magmatic and hydrothermal analcime is not clear.

Most hydrothermal analcime, found in basalt, is nearly a pure sodium analcime, with only traces of Ca, K, Cs and no Ba, Sr, Mg and Fe. There are a considerable number of chemically analyzed specimens that indicate a complete calcium-sodium series between wairakite and analcime (Tschernich, 1992). The general formula for the analcime group is Na₁₆Al₁₆Si₃₂O₉₆·16H₂O (Flanigen, 1981) or

 $(Na_2, Ca, Cs_2, Mg)_2[Al_2Si_4O_{12}] \cdot 2H_2O$ (Tschernich, 1992). There is a considerable range in the siliconaluminum content in analcime: $T_{Si} = Si/(Si + Al) = 0.60$ to 0.73; Si/Al = 1.93 to 2.81 (Tschernich, 1992).

Tschernich (1992) gives chemical compositions of analcime from different localities; these are listed in Table 6.2.

Analytical Methods

Mineral compositions of the zeolites were obtained using an CAMECA electron microprobe. To minimize Na loss, an unrastered electron beam 20 µm in diameter was used and operated at 15 kV, with a 10 nA beam current. Each element was analyzed for 20s. Four elements were analyzed at a time, each analysis consisting of three 20 s steps. To verify if the experimental conditions were minimizing Na loss, the same spot was analyzed for Na for 5 minutes with steps of 20 s. Na loss could not be detected during the first minute of the trial. To further minimize Na loss, Na was one of the four elements to be analyzed during the first 20s of analysis.

Analyses have low oxides sums (8.5 to 10 wt.% low) due to the presence of water in the structure of zeolites. All analyses correspond to analcime. The microprobe analyses were recalculated on a basis of 48 cations (Si + Al) in the aluminosilicate framework of analcime. The water content was calculated by stoichiometry to 16 moles per formula unit. Recalculation brought the oxide totals close to 100 wt.%. Analyses are presented in Table 6.3. Iron is reported as Fe³⁺; however, it is not known if iron is present as ferrous or as ferric ion.

The formulae for analcime of the Yogo dike can be summarized:

 $Na_{10,34+13,58}Ca_{0,46+2,80}K_{0,17+0,78}Fe_{0,00+0,22}Mg_{0,00+0,20}Sr_{0,00+0,12}[Al_{15,75+17,49}Si_{30,51+32,25}O_{94,.95+95,86}]\cdot 16H_2O$

 Table 6.2: Chemical compositions of analcime from different localities (all references from Tschernich, 1992).

LOCALITY	ANALCIME COMPOSITION	REFERENCE
Val di Fassa, Trento, Italy	$Na_{1.86}K_{0.02}[AI_{1.90}Si_{4.10}O_{12}] xH_2O$	Mazzi and Galli (1978)
Cyclopean Islands, Catania, Italy	$Na_{1.89}Ca_{0.07}[Al_{2.04}Si_{3.95}O_{12}] xH_2O$	Mazzi and Galli (1978)
Sugashima, Mie Prefecture, Japan	$Na_{1.85}Ca_{0.14}Mg_{0.53}[Al_{1.98}Fe_{0.04}Si_{3.93}O_{12}] 2.17H_2O$	Harada <i>et al</i> . (1972)
Tanzawa Mountains, Japan	$Na_{0.93}Ca_{0.48}Mg_{0.04}K_{0.01}[Al_{1.84}Si_{4.10}O_{12}]\ 2.18H_2O$	Seki and Oki (1969)
	$Na_{1.55}Ca_{0.11}Mg_{0.08}K_{0.01}[Al_{1.75}Si_{4.21}O_{12}] 2.19H_2O$	
Yellow Lake, Olalla, British Columbia, Canada	$Na_{1.84}K_{0.05}Ca_{0.04}[Al_{1.96}Si_{4.05}O_{12}] xH_2O$	
Bernic Lake, Manitoba, Canada	$Na_{1.01}Cs_{0.64}K_{0.02}Cs_{0.64}[Al_{1.70}Si_{4.30}O_{12}] \ 1.22H_2O$	Cerny (1972)

	Sample Y-12e-2; from ocellus						Sample Y-12e-6; from ocellus			
	1	2	3	4	5	6	1	а	2	
SiO ₂	52.40	53.13	52.83	52.92	52.09	53.07	53.15	52.62	52.99	
Al ₂ O ₃	24.79	24.41	24.21	24.41	24.89	24.54	24.24	24.56	24.55	
Fe ₂ O ₃	0.13	0.08	0.05	0.02	0.00	0.00	0.08	0.00	0.07	
MgO	0.09	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	
CaO	4.45	3.34	1.46	2.72	2.95	3.69	2.04	2.92	2.90	
SrO	0.00	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.00	
BaO	0.00	0.04	0.00	0.00	0.01	0.05	0.04	0.00	0.01	
Na ₂ O	9.46	10.50	11.86	10.97	10.99	10.34	11.36	10.83	10.54	
K ₂ O	0.30	0.25	0.36	0.29	0.34	0.28	0.35	0.31	0.31	
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.00	
H ₂ O*	8.16	8.19	8.13	8.16	8.14	8.19	8.17	8.15	8.19	
TOTAL	99.79	99.94	99.28	99.50	99.41	100.16	99.43	99.44	99.56	
Si ⁴⁺	30.78	31.12	31.15	31.09	30.71	31.07	31.20	30.97	31.03	
Al ³⁺	17.16	16.85	16.83	16.90	17.29	16.93	16.77	17.03	16.94	
Fe ³⁺	0.06	0.04	0.02	0.01	0.00	0.00	0.04	0.00	0.03	
Mg ²⁺	0.08	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	
Ba ²⁺	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	
Sr ²⁺	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	
Mn ²⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	
Na^+	10.77	11.92	13.56	12.50	12.56	11.74	12.93	12.36	11.97	
K^+	0.22	0.19	0.27	0.22	0.26	0.21	0.26	0.23	0.23	
Ca ²⁺	2.80	2.10	0.92	1.71	1.86	2.31	1.28	1.84	1.82	
Interframe catsum	13.87	14.22	14.88	14.43	14.68	14.27	14.48	14.45	14.02	
Catsum	61.87	62.23	62.88	62.43	62.68	62.27	62.49	62.45	62.02	
Vacancies pfu	2.13	1.77	1.12	1.57	1.32	1.73	1.51	1.55	1.98	
0	95.77	95.72	95.55	95.61	95.63	95.83	95.49	95.64	95.43	
Si/(Si+Al)	0.64	0.65	0.65	0.65	0.64	0.65	0.65	0.65	0.65	
Si/Al	1.79	1.85	1.85	1.84	1.78	1.84	1.86	1.82	1.83	

Table 6.3: Microprobe analyses of analcime from the Yogo dike (calculated on 48 [Si + Al + Fe^{3+}]).

*H₂O calculated for charge balance.

-	Sample `	Y-12e-6; fr	om ocellus		Sa				
<u> </u>	3	4	5	1	2	3	4	5	6
SiO ₂	53.62	52.96	53.60	54.08	53.81	51.79	54.34	54.58	53.29
Al ₂ O ₃	23.74	24.40	23.78	23.92	23.65	25.19	23.54	22.61	23.46
Fe ₂ O ₃	0.00	0.02	0.01	0.15	0.03	0.49	0.16	0.33	0.22
MgO	0.00	0.01	0.05	0.00	0.00	0.23	0.07	0.16	0.16
CaO	1.52	3.43	2.89	1.73	2.01	2.71	1.73	0.72	1.97
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BaO	0.00	0.01	0.00	0.01	0.02	0.06	0.03	0.04	0.00
Na ₂ O	11.74	10.42	10.64	11.44	11.34	9.03	11.53	11.85	.10.61
K ₂ O	0.33	0.29	0.22	0.33	0.23	1.06	0.25	0.35	0.59
MnO	0.00	0.04	0.00	0.00	0.00	0.00	0.05	0.00	0.08
H ₂ O*	8.16	8.17	8.16	8.22	8.16	8.14	8.20	8.12	8.09
TOTAL	99.11	99.75	99.35	99.89	99.26	98.74	99.92	98.78	98.49
Si ⁴⁺	31.54	31.10	31.52	31.51	31.61	30.37	31.73	32.15	31.54
Al ³⁺	16.46	16.89	16.48	16.43	16.38	17.41	16.20	15.70	16.36
Fe ³⁺	0.00	0.01	0.00	0.07	0.01	0.22	0.07	0.15	0.10
Mg ²⁺	0.00	0.01	0.04	0.00	0.00	0.20	0.06	0.14	0.14
Ba ²⁺	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.00
Sr ²⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn ²⁺	0.00	0.02	0.00	0.00	0.00	0.00	0.02	0.00	0.04
Na [†]	13.39	11.86	12.13	12.92	12.92	10.27	13.05	13.54	12.17
K^+	0.25	0.22	0.17	0.25	0.17	0.79	0.19	0.26	0.45
Ca ²⁺	0.96	2.16	1.82	1.08	1.27	1.70	1.08	0.45	1.25
Interframe catsum	14.60	14.27	14.16	14.25	14.36	12.97	14.41	14.40	14.05
Catsum	62.60	62.27	62.16	62.26	62.36	60.97	62.41	62.40	62.05
Vacancies pfu	1.40	1.73	1.84	1.74	1.64	3.03	1.59	1.60	1.95
0	95.55	95.78	95.77	95.42	95.62	95.63	95.66	95.58	95.51
Si/(Si+Al)	0.66	0.65	0.66	0.66	0.66	0.64	0.66	0.67	0.66
Si/Al	1.92	1.84	1.91	1.92	1.93	1.74	1.96	2.05	1.93

Table 6.3 (continued): Analyses of analcime from the Yogo dike (calculated on 48 [Si + Al + Fe^{3+}]).

 $*H_2O$ calculated for charge balance.

or for comparison with literature analyses, often presented based on (Si + Al) = 6:

 $Na_{1,29-1,70}Ca_{0,06-0.35}K_{0,02-0.10}Fe_{0,00-0.03}Mg_{0,00-0.03}Sr_{0,00-0.02}[Al_{1,97-2,19}Si_{3,81-4,03}O_{11,87-11,98}]\cdot 2H_2O.$

The totals of inter-framework cations from the Yogo ouachitite vary between 12.97 and 14.68, thus leaving a vacancy of 3.03 to 1.32 cations. Ca is the main cation to substitute for Na in this site and occupies between 0.45 to 2.80 of the site. K and Mg are the other cations to substitute for Na in minor amounts. BaO (≤ 0.06 wt.%) and MnO (≤ 0.08 wt.%) are below the detection limits or only slightly higher. SrO is significant in only one sample with 0.36 wt.% SrO.

The Si/Al ratio varies between 1.74 and 2.05 with values less than 1.93 except for two samples. This is lower than the ratio given by Tschernich (1992) of 1.93 to 2.81 for analcime. The silica site seems to be partially filled by Al. The Si/(Si + Al) ratio shows a small compositional range from 0.64 to 0.67.

In summary, the zeolite found in the Yogo dike is analcime in composition with a small component towards the wairkite end-member (Ca-rich end-member of the series). The framework seems to be undersaturated with respect to Si. The analcime is barium-poor and only one sample has strontium significantly over the detection limit.

6.5 Sapphire

6.5.1 Colour of Sapphire

Most people think of sapphires as blue gemstones; however, sapphires can be found in any colour except red; they are then called rubies. Sapphires can be colourless, yellow, orange (padparadscha sapphire),

orange-red, brown, green, purple-violet, pink and black. Some stones have more than one colour and they are then referred to as particoloured sapphires. Sapphire is dichroic and will show a different color or intensity of color when viewed parallel and perpendicular to the *c* axis. Thus sapphire can appear to be blue perpendicular to the *c* axis and green, greeenish blue or even greenish yellow in the other direction. Blue coloured sapphires are often described by locality names such as Kashmir blue, Burma blue, etc. The best Kashmir sapphires have a purplish blue (so-called cornflower blue) colour with a velvety appearance. This colour commands very high prices, and (Kashmir) stones with this colour are the highest priced sapphires. Although this area is no longer mined for sapphire, stones from Burma, Sri Lanka, and Thailand that have the same colour are often referred to as Kashmir blue. Burma stones have a fine rich blue or violet-blue (so-called royal blue) colour. High quality sapphires (as well as rubies) from Burma and Kashmir are extremely rare. Ceylon blue is a common name used in the trade. It refers to brilliant light-purplish blue to pale gray-blue stones. Ceylon sapphires are usually paler than Kashmir, Burma, Australian and Thai sapphires. Australian and Thai sapphires. Australian and Thai sapphires to medium dark with some gray. Siam or Siamese blue often refers to dark blue and inky to almost black stones although very fine coloured stones are also found in these two areas.

6.5.2 Cause of Colour in Sapphire

Sapphire owes its colours to charge-transfer phenomena. Charge-transfer occurs when an electron jumps from one atom to another. Such a charge-transfer often involves an atom of oxygen and a metallic ion such as Fe^{3+} , Fe^{2+} , Ti^{4+} . The colour results from light absorbed through the transfer of electrons from the oxygen ions to the iron ion. (Fritsch and Rossman, 1988). Usually oxygen to metal charge-transfer absorptions are centered in the near ultraviolet and are broad enough to extend into the blue end of the visible spectrum, producing yellow to orange to brown colors. (Fritsch and Rossman, 1988). Yellow sapphire derives its colour from this type of charge transfer.

In some instances, two metal ions separated by an oxygen ion can exchange electrons and this process is called intervalence charge-transfer. In blue sapphire, interactions between Fe^{2+} and Ti^{4+} gives sapphire its colour. According to Fritsch and Rossman (1988), intervalence charge-transfer shows extreme directionality, which usually causes strong pleochroism.

6.5.3 Composition of Yogo Sapphires

The Yogo sapphires in this study were separated into visually distinct colour grades (Table 6.4). Yogo sapphires are principally cornflower blue (which could be described as blue with a small violet component), violet blue, and violet. A small percentage of the production (approximately 10%) is purple blue and purple. Only a few rubies have been found during operation of the mine.

The Yogo sapphires were analyzed for major elements using an electron microprobe with the experimental conditions given in Appendix E. Analyses are presented in Table 6.5. Yogo sapphires have very few impurities. Iron was the most common impurity (0.41 to 0.67 wt.% Fe₂O₃), with traces of titanium (0.02 to 0.05 wt.% TiO₂) and chromium (0.03 to 0.08 wt.% Cr₂O₃) for purple sapphires. Other elements analyzed are at the detection limit of the electron microprobe (about 0.01 wt.% for each oxide). No difference was discernible between the colours in terms of major element geochemistry. Further analysis of the traces (Mn, V, Ti) by another method, such as proton induced X-Ray emission (PIXE), could shed more light on the cause of colour of the Yogo sapphire.

Table 6.4: Colour grades of Yogo sapphire.

Colour Number	Colour	Sample		
la	Purple	۵		
1b	Light purple			
2	Purple blue			
3	Violet	0		
4	Violet blue			
5	Very light violet <u>+</u> purple			
6	Dark violet blue			
7	Cornflower blue	0		
8	Cornflower blue	0		
9	Cornflower blue (violet decreases from 7 to 9, but subtle)	0		
10	Light cornflower blue	0		
11	Blue	0		
12	Light blue and light violet			
13	Greyish blues			
14	Not coloured			
16	Not gem quality			

Ouality	, , 16	G16c-1	98.24	0.48	0.03	0.00	0.00	0.00	0.01	98.76	Purple	15	G15c-1	98.50	0.51	0.03	0.03	0.00	0.01	0.02	90.09
Not Gem	16	G16a-1	98.01	0.52	0.03	0.00	0.00	0.00	0.01	98.58	Light]	15	G15a-1	97.04	0.44	0.04	0.03	0.00	0.01	0.02	97.58
ne	11	GI1c-1	99.28	0.65	0.04	0.00	0.01	0.00	0.01	66.66	e Blue	2	G2b-2	99.57	0.43	0.05	0.07	0.01	0.00	0.02	100.13
BI	11	G11a-1	99.07	0.67	0.04	0.00	0.00	0.00	0.01	99.80	Purpl	2	G2b-1	100.11	0.42	0.05	0.08	0.00	0.01	0.02	100.68
ver Blue	6	G9c-1	96.66	0.51	0.04	0.00	0.00	0.00	0.02	100.54	e Blue	2	G2a-2	99.10	0.53	0.04	0.08	0.00	0.01	0.02	99.78
Comflox	6	G9a-1	99.19	0.47	0.04	0.00	0.00	0.00	0.02	99.72	Purple	2	G2a-1	100.24	0.52	0.04	0.08	0.00	0.00	0.02	100.90
ver Blue	∞	G8c-1	99.48	0.57	0.04	0.01	0.00	0.01	0.02	100.13	olet Blue	4	G4c-1	98.97	0.50	0.05	0.01	0.00	0.01	0.01	99.55
Comflov	8	G8b-1	98.86	0.63	0.05	0.00	0.00	0.00	0.02	99.55	Light Vid	4	G4a-1	99.58	0.56	0.05	0.03	0.00	0.01	0.02	100.24
er Rhie	7	G78b-1	98.49	0.41	0.04	0.01	0.00	0.00	0.01	98.95	Violet Blue	5	G5c-1	99.40	0.52	0.04	0.02	0.00	0.00	0.02	100.00
Comflow	7	G78-1	98.67	0.64	0.02	0.01	0.00	0.00	0.01	99.34	Very Light	5	G5a-1	99.14	0.56	0.05	0.01	0.00	0.00	0.02	99.78
Colour	Colour Code	Sample	Al ₂ O ₃	Fe_2O_3	TiO ₂	Cr_2O_3	MnO	V_2O_3	MgO	TOTAL	Colour	Color Code	Sample	Al ₂ O ₃	Fe_2O_3	TiO ₂	Cr_2O_3	MnO	V_2O_3	MgO	TOTAL

Table 6.5: Chemical compositions of Yogo sapphires.

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6.5.4 Comparison Between the Yogo Sapphires and Other Sapphires

Yogo sapphires have lower iron content than Australian sapphires (Table 6.6) and higher iron content than Sri Lankan sapphires, according to these few analyses. Titanium content is in the same range as for these two localities. Chromium is obviously responsible for the colour of the purple Yogo sapphires. No ruby was analyzed, thus I can not compare Yogo rubies (which are extremely rare) with other rubies worldwide.

6.6 Mineral Chemistry of a Garnet-Pyroxene-(Plagioclase) Granulite Xenolith

A small $(4 \times 1 \text{ cm})$, unusual xenolith was found in one of the samples. In hand sample, the xenolith has spotty flesh-coloured grains. Thin section study reveals that the xenolith is composed of garnets with interstitial clinopyroxenes and few plagioclases. The texture is granoblastic polygonal. Garnets show resorption features such as embayments and are rimmed by brownish-green fibrous keliphytic rims (Figure 6.6). The xenolith is surrounded by a rim rich in green spinel (pleonaste). The assemblage garnetpyroxene-plagioclase belongs to the higher pressure garnet granulite sub-facies of the granulite facies. The transition from the garnet granulite to the eclogite facies is marked by the disappearance of plagioclase in the mineral assemblage. This is the only xenolith of this type to have been found in the rock.

Garnet analyses are presented in Table 6.7, pyroxene analyses in Table 6.8. A few plagioclase grains were also analyzed (Table 6.9) with the same experimental conditions and standards as for the garnets and pyroxenes to determine their calcicity. Operating conditions for the CAMECA electron microprobe used to analyze these minerals are given in Appendix F.

Oxides	Australian (Mumn	n Sapphires ne, 1988)	Sapphires from Elahera, Sri Lanka (Hughes, 1990)				
	Pale Blue	Blue-Green	Blue	Blue			
Al ₂ O ₃	96.9	96.4	99.43	99.71			
Fe ₂ O ₃	1.00	1.0	n.d.	n.d.			
FeO	n.d.	n.d.	0.15	0.17			
TiO ₂	0.05	0.18	0.01	0.01			
Cr ₂ O ₃	<0.02	<0.02	n.d.	n.d.			
MnO	<0.02	<0.02	n.d.	n.d.			
V_2O_3	n.d.	n.d.	n.d.	n.d.			
MgO	<0.05	<0.05	n.d.	0.02			
SiO ₂	0.16	0.18	0.06	0.03			
CaO	<0.05	<0.05	0.02	n.d.			
TOTAL	98.10	97.7	99.67	99.97			

Table 6.6: Chemical compositions of sapphires from Australia and Sri Lanka.



Figure 6.6: BSE image of the granulite xenolith. The light grey mineral is pyroxene, the medium grey is kelyphitic alteration of garnet, the dark grey is plagioclase, and the white mineral is pyrite. A garnet surrounded by a kelyphitic rim is shown in the lower right section of the photograph.
The relative amounts of coexisting pyroxenes, garnets and plagioclases present in the mineral assemblage, as well as their mineral compositions, depend upon their pressure and temperature of equilibration as well as the bulk rock composition. At the lower boundary of the garnet granulite facies, plagioclase is abundant while garnet is scarce. Green and Ringwood (1967) observed that plagioclase decreases as pressure and temperature increases. At the upper limit of the garnet granulite facies, plagioclase is a minor component of the assemblage. The complete disappearance of plagioclase in the rock marks the transition, by definition, between the granulite and eclogite facies. However, the modal content of plagioclase in mafic rocks is lower than in felsic ones, so the whole rock geochemistry should also be taken into account. This will be discussed further in the chapter on geothermobarometry based on the mineral chemistry presented here.

6.6.1 Garnet Composition

The garnet formula was calculated on a basis of 24 anions (O) and 16 cations. Iron was analyzed as FeO and the Fe₂O₃ content was calculated based on charge balance and stoichiometry. The garnets show a homogeneous composition. They are chromium-poor pyropes (54.2 to 59.0% pyrope) with subordinate almandine, grossular, andradite and spessartine contents (representing, respectively 21.4 to 23.6, 8.1 to 14.6, 6.6 to 11.1 and 0.28 to 0.43% of the garnet molecule). Fe₂O₃ content is influenced by the quality of analyses, especially by the accuracy of the SiO₂ content since the charge balance equation will favor more Fe³⁺ in case of a low SiO₂ content. Table 6.7 shows that the total of the trivalent cations in the *Y* site of the garnet (X₆Y₄Z₆O₂₄) is high (4.15 to 4.27) and sum of the divalent cations in the *X* site is low (5.73 to 5.85). This could be due to analytical errors and will affect the distribution of garnet end-members, especially andradite (Ca₃Fe³⁺₂Si₃O₁₂). Due to difficulties in estimating ferrous and ferric iron, garnet analyses are often presented in terms of the three end-members pyrope, almandine and grossular by calculating the ratios Mg/(Mg + Fe_{total} + Ca), Fe_{total}/(Mg + Fe_{total} + Ca) and Ca/(Mg + Fe_{total} + Ca), respectively. If this

	G1	G2	G3	G4	G5	G 6	G7a	G7b
SiO ₂	40.25	40.32	40.01	39.95	40.29	39.77	39.43	39.91
Al ₂ O ₃	23.85	23.50	23.42	23.40	23.67	23.60	23.74	23.40
FeO	11.02	11.56	11.40	10.81	11.36	10.73	10.12	10.65
FeO ₃	3.11	2.52	2.64	3.01	3.01	3.83	4.32	3.73
TiO ₂	0.05	0.04	0.05	0.05	0.04	0.06	0.06	0.05
Cr ₂ O ₃	0.00	0.00	0.00	0.01	0.02	0.00	0.03	0.05
MnO	0.13	0.18	0.16	0.20	0.14	0.20	0.18	0.20
MgO	15.00	14.87	14.56	14.52	14.91	14.95	15.61	15.51
CaO	7.99	7.73	8.06	8.38	7.84	7.75	7.08	7.20
Na ₂ O	0.01	0.02	0.01	0.04	0.02	0.02	0.00	0.01
Total	101.41	100.74	100.31	100.37	100.30	100.91	100.57	100.71
Si ⁺	5.80	5.85	5.84	5.82	5.82	5.77	5.73	5.79
Al ^{IV}	0.20	0.15	0.16	0.18	0.18	0.23	0.28	0.21
Sum	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
3.77								
Al	3.85	3.87	3.87	3.84	3.85	3.81	3.79	3.79
Fe ³⁺	0.34	0.28	0.29	0.33	0.33	0.42	0.47	0.41
Ti ⁴⁺	0.01	0.00	0.01	0.01	0.00	0.01	0.01	0.01
Cr ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Sum	4.20	4.15	4.16	4.18	4.18	4.23	4.27	4.21
•								
Mg ²⁺	3.22	3.22	3.17	3.16	3.21	3.23	3.38	3.35
Fe^{2+}	1.33	1.40	1.39	1.32	1.37	1.30	1.23	1.29
Ca ²⁺	1.23	1.20	1.26	1.31	1.21	1.21	1.10	1.12
Mn ²⁺	0.02	0.02	0.02	0.03	0.02	0.03	0.02	0.03
Na^+	0.00	0.01	0.00	0.01	0.01	0.01	0.00	0.00
Sum	5.80	5.85	5.84	5.82	5.82	5.77	5.73	5.79
Pyrope (%)	55.56	55.05	54.25	54.34	55.23	56.08	58.96	57.93
Almandine (%)	22.89	24.01	23.83	22.69	23.61	22.58	21.44	22.31
Spessartine (%)	0.28	0.38	0.34	0.43	0.29	0.43	0.38	0.43
Andratite (%)	8.15	6.72	7.07	8.04	7.92	10.05	11.22	9.79
Grossular (%)	13.12	13.84	14.51	14.50	12.95	10.85	7.99	9.54
mg	65.94	65.72	65.34	65.68	65.39	65.27	66.52	66.38
Fe/(Fe+Mg+Ca)	27.20	27.52	27.51	26.97	27.75	27.93	27.52	27.53
Mg/(Fe+Mg+Ca)	52.65	52.76	51.86	51.62	52.43	52.50	54.67	54.34
Ca/(Fe+Mg+Ca)	20.16	19.71	20.63	21.41	19.81	19.57	17.81	18.13

Table 6.7: Chemical composition of garnets from the granulite xenolith (in wt.%), recalculated on the basis of 16 cations and 24 O per formula unit.

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scheme is followed, the garnet from the granulite has the following composition: 51.62 to 54.67% pyrope, 27.20 to 27.93% almandine, and 17.81 to 21.41% grossular (Table 6.7).

The plagioclase content of the xenolith is low (< 10% by volume) which suggests that the xenolith equilibrated at pressure and temperature of the upper granulite facies, close to the boundary with the eclogite facies. Garnets from the granulite xenolith were compared to eclogitic garnets by plotting them on the ternary diagram of Coleman *et al.* (1965) (Fig. 6.7). They are similar in composition to garnets of eclogite group A (eclogites in kimberlites and other ultramafic rocks). They also are similar in composition to garnets found in corganite and corgaspinite (Mazzone and Haggerty, 1986) xenoliths from the Jagersfontein kimberlite pipe, South Africa. These xenoliths contain, respectively, corundum-garnet and corundum-garnet-spinel (pleonaste). Pyrope instability at low pressure causes its breakdown into a mixture of either hornblende, plagioclase and iron ore, or fibrous amphibole and green biotite (Deer *et al.*, 1978). The kelyphitic rims consist of these breakdown products.

6.6.2 Pyroxene Compositions

Formula recalculation of pyroxenes is based on 6 anions (O) and 4 cations (Table 6.8). Cation distribution was calculated according to Morimoto's (1988) approach. Distribution of Mg and Fe²⁺ between the *M*1 and *M*2 sites is somewhat arbritary as it depends on the temperature and cooling rate of the pyroxene (Robinson, 1981). Pyroxenes of the garnet-plagioclase granulite xenolith are classified as magnesian aluminian sodian diopside. They are Cr-poor (< 0.09 wt.% Cr₂O₃), Ti-poor (< 0.5 wt.% TiO₂), Al-rich (8.2 wt.% Al₂O₃). They are expressed in term of the end-members acmite, jadeite, Ti-Tschermak, Fe-Tschermak, Ca-Tschermak, wollastonite, enstatite and ferrosilite in Table 6.9. The pyroxenes are rich in the Ca-Tschermak's component (14.1 to 15.1%) and poor in jadeite (2.4 to 4.6%) and acmite (5.7 to 7.9%). They are similar in composition to pyroxenes of pyroxene-spinel xenoliths as shown



Figure 6.7: Composition of garnets from the garnet-pyroxene-plagioclase granulite xenolith compared to eclogitic garnets from Coleman *et al.* (1965).

in Appendix E, analyses G10-1 to G10-9. The last ones, however, are poorer in Na₂O (< 0.64 wt.%), richer in TiO₂ (0.52 to 1.00 wt.%) and have a higher Al^{VI} content. Some pyroxene megacryst rims also have a composition similar to pyroxenes of the granulite xenolith. Pyroxene cores in the ouachitite are more Mg-rich (up to 18.4% MgO), Al-poor (usually less than 3% Al₂O₃), Na-poor (< 1% Na₂O) than the ones in the granulite. Some are Cr-rich (up to 1.6% Cr₂O₃), some are Cr-poor.

White (1964) compared pyroxenes from eclogites against pyroxenes from granulites. The former have a lower Tschermak's molecule component and a higher jadeite component than pyroxenes from granulites (Figure 6.8). These have a jadeite/Tschermak's molecule ratio less than 1/2 (White, 1964) while the same ratio is greater than 4/5 for eclogitic pyroxenes. Pyroxenes from the garnet-granulite xenolith were calculated in terms of the end-members acmite (NaFe³⁺Si₂O₆), jadeite (NaAlSi₂O₆), Tschermak's ((Ca,Mg)AlAlSiO₆), hedenbergite (CaFeSi₂O₆) and diopside (CaMgSi₂O₆) according to White's (1964) scheme. Acmite was calculated first, using all the Fe³⁺. The Na remaining was then assigned to jadeite. The Tschermak's component was calculated using the remaining Al content. Some Mg was assigned to the Tschermak's molecule so that an equal amount of Ca and Mg enter the diopside components (see Tables 6.9 and 6.10). When plotted on Figure 6.8, the pyroxenes fall in the granulite field. Their jadeite content is lower than eclogitic pyroxenes and their Tschermak's content is higher. We can see on the graph a sympathetic relationship between the jadeite and the Tschermak's content.

	Sample	Sample Y-44a: Garnet-Pyroxene-Plagioclase Xenolith						imple Y-4 hibole-Pyr Xenolith	4b: oxene
	PY2	PY3	PY4	P5	PY5	PY7	PY10	PY11	PY12
SiO ₂	50.07	49.77	50.06	49.56	49.53	49.26	45.59	50.14	41.30
Al ₂ O ₃	8.22	8.20	8.21	8.14	8.17	7.86	11.93	5.87	12.72
FeO	2.27	2.18	2.28	1.85	1.74	3.18	0.58	4.54	0.00
Fe ₂ O ₃	2.10	2.25	2.07	2.64	2.86	1.19	5.83	4.19	7.83
TiO ₂	0.46	0.44	0.47	0.49	0.51	0.47	0.90	0.39	2.13
Cr_2O_3	0.02	0.00	0.00	0.00	0.00	0.01	0.03	0.09	0.00
MnO	0.01	0.05	0.02	0.03	0.00	0.03	0.14	0.09	0.10
MgO	13.27	13.28	13.23	13.23	13.31	13.01	11.72	12.19	11.04
CaO	21.53	21.37	21.71	21.48	21.46	21.03	21.90	20.34	23.69
Na ₂ O	1.46	1.43	1.42	1.45	1.45	1.29	1.22	1.70	0.33
Total	99.41	98.97	99.47	98.87	99.03	97.33	99.84	99.54	99.14
Si⁺	1.83	1.83	1.83	1.83	1.82	1.84	1.68	1.86	1.56
Al ^{IV}	0.17	0.17	0.17	0.18	0.18	0.16	0.32	0.14	0.45
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
AI ^{VI}	0.19	0.19	0.19	0.18	0.18	0.19	0.20	0.12	0.12
Fe ³⁺	0.06	0.06	0.06	0.07	0.08	0.03	0.16	0.12	0.22
Ti ⁴⁺	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.01	0.06
Cr ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mg ²⁺	0.72	0.73	0.72	0.73	0.73	0.73	0.62	0.68	0.60
Fe ²⁺	0.02	0.01	0.02	0.01	0.00	0.04	0.00	0.07	0.00
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Μσ ²⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.02
Fe ²⁺	0.05	0.05	0.05	0.05	0.05	0.06	0.02	0.07	0.00
Mn ²⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca^{2+}	0.84	0.84	0.85	0.85	0.85	0.84	0.86	0.81	0.96
Na ⁺	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.12	0.02
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		-		·			·		
Ca	49.79	49.50	50.03	49.71	49.47	49.50	51.12	46.36	53.08
Mg	42.71	42.80	42.45	42.61	42.74	42.63	38.05	38.68	34.43
Fe	7.49	7.70	7.52	7.69	7.79	7.87	10.83	14.96	12.49
mg	85.08	84.95	85.04	84.81	84.59	84.52	78.22	72.35	73.63

Table 6.8: Chemical compositions of pyroxenes from xenoliths (in wt.%) calculated on the basis of 4 cations and 6 O.

<u></u>		PY2	PY3	PY4	P5	PY5
Acmite	NaFe ³⁺ Si ₂ O ₆	5.8	6.2	5.7	7.3	7.9
Jadeite	NaAlSi2O6	4.6	4.0	4.4	3.1	2.4
Ti-Tschermak's	CaTiAlAlO ₆	1.3	1.2	1.3	1.4	1.4
Fe-Tschermak's	CaFe ³⁺ AlSiO ₆	0.0	0.0	0.0	0.0	0.0
Cr-Tschermak's	CaCrAlSiO ₆	0.1	0.0	0.0	0.0	0.0
Ca-Tschermak's	CaAlAlSiO ₆	14.1	14.6	14.2	14.7	15.1
Wollastonite	Ca ₂ Si ₂ O ₆	34.5	34.2	34.8	34.3	34.0
Enstatite	$Mg_2Si_2O_6$	36.2	36.4	36.1	36.3	36.5
Ferrosilite	$Fe_2Si_2O_6$	3.5	3.4	3.5	2.9	2.7

Table 6.9: Pyroxene compositions in terms of end members (mol.%).

	PY2	PY3	PY4	P5	PY5
Acmite (NaFe ³⁺ Si ₂ O ₆)	0.058	0.062	0.057	0.073	0.079
Jadeite (NaAlSi ₂ O ₆)	0.046	0.040	0.044	0.031	0.024
Tschermak's ((Ca,Mg)AlAlSiO ₆)	0.154	0.158	0.155	0.161	0.165
Diopside (CaMgSi ₂ O ₆)	0.672	0.673	0.674	0.678	0.678
Hedenbergite (CaFeSi ₂ O ₆)	0.069	0.067	0.070	0.057	0.054

 Table 6.10:
 End member contents of the pyroxenes from the granulite, recalculated according to White (1964).



Figure 6.8: Graph of mol.% jadeite against Tschermak's molecule showing the different compositions of eclogitic and granulitic clinopyroxenes (from White, 1964). The lower line represents a Jd/Ts ratio of 1/2. Eclogitic pyroxenes have a Jd/Ts ratio greater than 4/5 (upper line).

6.6.3 Plagioclase Composition

The xenolith also contains some rare plagioclase. An estimate of their composition was obtained by analyzing them with the same standards and analytical conditions as for the garnets and pyroxenes. They have a composition of An_{44-45} , or andesine (Table 6.11).

6.6.4 Calculated Chemistry of the Garnet-Granulite Xenolith

The whole-rock geochemistry of the granulite xenolith was calculated based on the composition and mode of the minerals present and is presented in Table 6.12 for three different modes, to see the variations caused by errors on the visual estimates.

	Y-44a	Y44b	Y-33a54	Y-33a55	Y-33a56	Y-33a57	Y-33a58
SiO ₂	56.01	56.28	53.27	53.43	53.51	53.51	53.70
Al ₂ O ₃	26.72	27.32	29.02	28.93	29.01	29.30	29.06
FeO	0.12	0.10	0.13	0.08	0.12	0.08	0.10
MgO	0.04	0.03	0.02	0.02	0.02	0.02	0.01
MnO	0.02	0.00	0.00	0.02	0.06	0.00	0.00
Cr_2O_3	0.01	0.04	0.00	0.05	0.00	0.00	0.00
TiO ₂	0.02	0.00	0.04	0.03	0.01	0.03	0.02
Na ₂ O	6.15	6.06	5.04	5.13	5.08	5.15	5.07
CaO	8.90	9.07	11.20	11.12	11.11	11.18	11.17
Total	97.99	98.90	98.72	98.81	98.92	99.27	99.13
Si ⁴⁺	10.24	10.20	9.75	9.76	9.77	9.73	9.78
Al ³⁺	5.76	5.83	6.26	6.23	6.24	6.28	6.24
Fe ²⁺	0.02	0.02	0.02	0.01	0.02	0.01	0.02
Mg ²⁺	0.01	0.01	0.01	0.01	0.01	0.01	0.00
Mn ²⁺	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Cr ³⁺	0.00	0.01	0.00	0.01	0.00	0.00	0.00
Ti⁴⁺	0.00	0.00	0.01	0.00	0.00	0.00	0.00
Sum	16.04	16.06	16.03	16.03	16.04	16.04	16.03
Ca ²⁺	1.74	1.76	2.20	2.18	2.17	2.18	2.18
Na^+	2.18	2.13	1.79	1.82	1.80	1.82	1.79
Sum	3.93	3.89	3.98	4.00	3.97	4.00	3.97
An	44.4	45.3	55.1	54.5	54.7	54.5	54.9
Ab	55.6	54.7	44.9	45.5	45.3	45.5	45.1
	Ande	esine	e Labradori		rite Labradorite		

Table 6.11: Chemical compositions (in wt.%) of plagioclase feldspars from two xenoliths. Analyses are recalculated on the basis of 32 O, all Fe as Fe²⁺.

		Average (wt.%)	Calculated Whole Rock Chemistry for the following Garnet, Pyroxene, and Plagioclase Modes (%).			
	Garnet	Pyroxene	Plagioclase	(50, 40, 10)	(60, 35, 5)	(45, 50, 5)	
SiO ₂	39.99	49.80	56.15	45.53	44.23	45.70	
Al ₂ O ₃	23.57	8.19	27.02	17.76	18.36	16.05	
FeO	13.90	4.20	0.11	8.64	9.82	8.36	
TiO ₂	0.05	0.47	0.01	0.22	0.20	0.26	
Cr ₂ O ₃	0.01	0.00	0.03	0.01	0.01	0.01	
MnO	0.17	0.02	0.01	0.10	0.11	0.09	
MgO	14.99	13.27	0.03	12.81	13.64	13.38	
CaO	7.75	21.51	8.98	13.38	12.63	14.69	
Na ₂ O	0.02	1.44	6.16	1.20	0.82	1.04	
Total	100.46	98.90	98.49	99.64	99.82	99.58	

Table 6.12: Calculated whole rock composition of the granulite xenolith.

7. MINERAL AND FLUID INCLUSIONS IN SAPPHIRES

7.1 Mineral Inclusions

Mineral inclusions are rare in the Yogo sapphires. Koivula (personnal communication) found crystals of rutile, calcite, analcite and biotite in cut Yogo sapphires. During a conversation with Richard Hughes, author of the recent book on "Corundum", he mentioned that many of the stones studied by Koivula were not from the Yogo deposit.

Many sapphires were looked at under a binocular microscope by the author. Two thick sections used to study fluid inclusions were observed using a transmitted light microscope. These sections are polished on both sides; because of the transparency of the sapphires, it is possible to focus on the top surface and then defocus until the bottom of the section is in view. Using this technique, any inclusions are readily discovered. A white globular inclusion (analcime?) was found in one section. A few sapphires were found to contain needles of a translucent reddish mineral (rutile?). Because these inclusions appeared to reach the surface of the sample they were studied with the Scanning Electron Microscope (SEM). However, none of the inclusions could be found at the surface of the sample. Many minerals found in sapphires observed with the SEM seem to occupy holes in the sapphires. Although the samples were ground and polished, some pits remain. The minerals found in these pits originated either with contamination from the grinding and polishing laps, or are remain of the Yogo rock attached to the sapphires. It is important to mention here that all the sapphires studied for inclusions are from Kelly Coulee and sapphires from this area do not have a coating of pleonaste spinel typical of those from the English and Middle Mines. Phases that are thought to be due to contamination are the following: Cu-Al-O-Zn-Ni, Ca-Fe-Ce-Al-O-Si-Fe, and possibly Al-O-Cu. Grains analyzed were small (approximately 2 to 5 microns) and Al and O are due to the

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backround mineral sapphire since the size of the beam is about 2 microns. Minerals identified that are thought to be coatings on the sapphires are phlogopite, analcime, barite, apatite, Cr-bearing magnetite, calcite and gypsum. All of these minerals (except gypsum) were identified in the dike rock. Other minerals that are probably inclusions in the sapphires are sphalerite, pyrite, wollastonite?, and needles of a mineral with the composition Al-O-Si, possibly kyanite. Although the Al and O may be from the sapphire kyanite is inferred because quartz could not coexist in equilibrium with corundum. None of these minerals were identified in the dike rock.

Based on this preliminary work, the few inclusions found in the Yogo sapphires indicate that they are xenocrysts, since neither kyanite or sphalerite were identified in the dike rock. More work needs to be done on the location and identification of inclusions in the Yogo sapphires

7.2 Fluid Inclusions

Fluid inclusions in the Yogo sapphires were studied by Roedder (1972). He found primary inclusions of liquid CO_2 containing a large bubble of gaseous CO_2 , plus two types of daughter minerals, equant and acicular. He also found that the CO_2 inclusions are under high pressure (approximately 70 atmospheres at room temperature). Tiny secondary inclusions were also found by Roedder. They were located around the primary ones and contain CO_2 liquid and a vapour that homogenized at about 31°C, and an unidentified birefringent plate or blade with an index of refraction slightly less than that of the enclosing sapphire. Roedder suggested (based on the fluid inclusions) that the sapphires crystallized under high pressure. The ascent of the sapphires in the magma causes the primary fluid inclusions to crack due to a lower confining pressure. Some of the fluid escaped and was trapped in tiny secondary inclusions.

A few good primary inclusions were found in two sapphires. R. Sherlock identified them as CO_2 inclusions, similar to the ones found by Roedder. These inclusions homogenized at 31.0° C and froze at - 56.6°C, indicating that they are pure CO_2 . Sherlock also found some melt inclusions. He tried to homogenize the inclusions in a furnace at temperatures up to approximately 1000°C (the temperature limit of the furnace), but they did not homogenize. He suggested that a higher temperature was needed. If homogenization is attained, the crystals are quenched and the resulting glass from the inclusions is analyzed. This gives some indication of the composition of the fluid in which the sapphire grew. Unfortunately, the equipment needed to do this research is not available at UBC.

Secondary inclusions were numerous in these two samples. They usually have a flat elongated shape, with a bubble in the middle. They are located near fractures and are oriented parallel to the growth zone of the sapphire crystal.

8. GEOTHERMOMETRY AND GEOBAROMETRY

8.1 Introduction

Geothermometers and geobarometers are based on the equilibria of two or more coexisting minerals. There are two types of geothermometers; the exchange thermometers, which are based on exchange reactions, and the solvus thermometers, based on the compositions of phases coexisting across a solvus (Spear, 1993). Geobarometers are usually based on net transfer reactions, that cause the production and consumption of phases (Spear, 1993). Net transfer reactions are pressure sensitive because they involve large volume changes. An example of exchange thermometer is the garnet-clinopyroxene Fe-Mg thermometer. A solvus thermometer often used is the two-pyroxene geothermometer, based on the distribution of Ca and Mg between coexisting clinopyroxene and orthopyroxene. Geobarometers are numerous (see list in Spear, 1993) and involved principally garnet coexisting with two or more other minerals. The garnet-plagioclaseclinopyroxene-quartz barometer is an example. Garnet is the most common mineral involved in exchange thermometers and net transfer equilibria (geobarometers). Unfortunately, garnet is not present in the Yogo dike and very few garnet-bearing xenoliths have been found in the rock. Dahy (1988) mentioned one kyanite-garnet (+ quartz and rutile) xenolith found during his study. The garnet-pyroxene-plagioclase granulite xenolith found during my field work and described in Sections 3.6.1 and 6.6 is probably one of the deepest xenoliths on which geothermometers can be applied. Cognate pyroxenite xenoliths are common in the rock and probably come from greater depth than the granulite xenolith, but presently there is no thermometer based on the variation of composition with temperature for the assemblage diopsidephlogopite. For this reason, the garnet-granulite xenolith was studied in detail to try to find out its depth of formation.

The chemistry of pyroxene and phlogopite can also be used to estimate their temperature and to a lesser extent, their pressure of formation.

8.2 P and T of the Transition from Granulite to Eclogite Facies

The presence of both garnet and plagioclase in the xenolith gives some constraints on its depth of formation. Garnet appears in granulite between 12 kbar (950°C) to 16 kbar (1200°C) and plagioclase disappears between 16 kbar (950°C) and 25 kbar (1250°C) (Muller *et al.*, 1977). The bulk chemistry of the rock is an important factor controlling the pressure at which plagioclase and garnet appear and also their modal contents in the assemblage garnet-pyroxene-plagioclase. The first appearance of garnet in the mineral assemblage is lower in silica deficient rocks (olivine normative) than in silica saturated rocks and lower in rocks with higher Fe/Mg ratios. The modal content of plagioclase is lower in rocks with higher Mg/Fe at a same pressure. Pressures for the plagioclase-out reaction at 1100°C range from 12 to 29 kbar, depending on the Ca/Na ratio and the bulk Na₂O content (Spear, 1993).

The xenolith whole rock chemistry calculated in Chapter 6.6.4 was compared to the material studied by Green and Ringwood (1967) and Irving (1974) during their high-pressure experiments. The granulite xenolith whole rock composition is similar to the olivine tholeiite (B) of Green and Ringwood (1967), except for the higher Al content (2.5 to 4 wt.% Al₂O₃) and lower Fe content (3 to 4 wt.% FeO) of the granulite xenolith. In their high-pressure experiments, plagioclase disappears at about 13.5 kbar at a temperature of 1100°C for this composition. The granulite xenolith has a composition intermediate between the garnet-plagioclase clinopyroxenite and garnet-clinopyroxenite of Irving (1974), but is somewhat closer to the latter. The garnets of the granulite xenolith are less magnesian (~15 wt.% MgO) than the garnet of the garnet clinopyroxenite (18 wt.% MgO) of Irving (1974), and the pyroxenes are slightly less aluminous (8.2 wt.% compared to 9.8 wt.% Al₂O₃). Clinopyroxenes of the garnet-plagioclase

clinopyroxenite are poorer in Mg (10.3 wt.% MgO compared to 15 wt.%), richer in Al (9.8 wt.% Al₂O₃ compared to 8.2 wt.%), Ti (1.2 wt.% TiO₂ versus 0.2 wt.%) and Fe (2.8 wt.% Fe₂O₃, 6.8 wt.% FeO compared to ~9 wt.% FeO) than pyroxenes of the granulite xenolith. Garnets are also poorer in Mg (10.2 wt.% MgO), and richer in Fe (2.1 wt.% Fe₂O₃, 16.5 wt.% FeO) than garnet of the granulite xenolith (~15 wt.% MgO, ~3 wt.% Fe₂O₃, and ~11 wt.% FeO). Plagioclase disappears at about 21 kbar at a temperature of 1100°C for the garnet-plagioclase clinopyroxenite and at about 13 kbar for the garnet clinopyroxenite. Because the pressure of disappearance of plagioclase increases with the Fe/Mg ratio, and the xenolith composition is closer to the garnet clinopyroxene composition, it can be inferred that the granulite xenolith crystallized at a pressure between 13 and 21 kbar, probably in the area of 15 kbar.

8.3 Change in Mineral Composition as a Function of T and P for the Assemblage Garnet-Pyroxene-Plagioclase

Green and Ringwood (1967) observed that plagioclase content in the assemblage garnet-clinopyroxeneplagioclase (garnet granulite) decreases as pressure and temperature increase. The mineral composition of the coexisting garnet, pyroxene and plagioclase is also affected. As pressure increases, the range of solid solution in plagioclase becomes increasingly restricted as the large volume anorthite component becomes unstable with respect to pyroxene or garnet (Spear, 1993). Plagioclase composition becomes more Narich, clinopyroxene becomes enriched in the Tschermak's (CaAlAlSiO₆) component and garnet becomes more pyropic. The jadeite (NaAlSi₂O₆) content of pyroxenes is low until plagioclase completely disappears. In the upper granulite facies, close to the transition with the eclogite facies, the Tschermak's molecule of the pyroxenes exsolves to form garnet as pressure increases. The increase of the garnet content relative to the pyroxene content is due to the smaller partial molar volume of Al₂O₃ in solution in garnet as compared to pyroxenes. In the binary system diopside-jadeite, the jadeite content of clinopyroxene increases as pressure increases and temperature decreases (Deer *et al.*, 1978). The jadeite content of clinopyroxene shows a sympathetic relation with the Ca-Tshermak's component. The system CaMgSi₂O₆-NaAlSi₃O₈-CaAl₂Si₂O₈ has been studied by Kushiro (1969, from Deer *et al.*, 1978) at 15, 20, 28 and 35 kbar at 1150°C. The clinopyroxene solid solution changes with increasing pressures from about Di_{76.9}Jd_{5.3}Ca-Ts_{17.8} (mol.%) at 15 kbar to Di_{75.1}Jd_{7.9}Ca-Ts₁₇ and Di_{61.1}Jd₂₇Ca-Ts_{11.9} at 20 and 28 kbar. Composition of the pyroxenes from the garnet granulite, expressed in term of their end-members (Tables 6.9, 6.10) and renormalized without the acmite and hedenbergite (Fe) end-members are similar to the composition obtained at 15 kbar during Kushiro's experiments.

The jadeite content, as well as the Ca-Tschermak's and $CaTiAl_2O_6$ contents, are also a function of the composition of the magma. As the *mg* value decreases, the jadeite content increases while the two other components decrease (Deer *et al.*, 1978).

The main characteristic of pyroxenes from granulites is their high Tschermak's molecule content (CaAlAlSiO₆). Eclogitic pyroxenes are also Al-rich, but the Al is mainly present as Al^{VI} in the jadeite component of omphacite, which is the typical pyroxene in eclogite. This pyroxene forms solid solution between jadeite and diopside with minor acmite and hedenbergite components, and usually negligible contents of the Cr, Mn and Ti end members (Smith, 1988). The Tschermak's molecule contains both tetrahedrally-coordinated and octahedrally-coordinated aluminum. The first one is unstable at low temperature and high pressure because it occupies a large volume compared to Al^{VI}. For this reason, the Tschermak's component is present mainly in pyroxenes that have crystallized at high temperature and moderate, rather than high pressures. The pure Ca-Tschermak's molecule is not stable below 1160°C and 12 kbars (Deer *et al.*, 1978), and has a relatively restricted pressure stability field, thus accounting for the

absence of the CaAl₂SiO₆ pyroxene in natural environments (Deer *et al.*, 1978). The stability field of CaAlAlSiO₆ (Deer *et al.*, 1978) is defined by the reactions:

$$CaAl_2Si_2O_8 + Ca_2Al_2SiO_7 + Al_2O_3 = CaAl_2SiO_6$$
(8.1)

anorthite + gehelenite + corundum = CaTs

$$CaAl_2SiO_6 = Ca_3Al_2Si_3O_{12} + 2Al_2O_3$$
 (8.2)

CaTs = grossular + corundum

These may be expressed by the following linear equations:

$$P(bars) = 12500 + 9.9 (T^{\circ}C - 1250)$$
(8.3)

$$P(bars) = 17500 + 63.8 (T^{\circ}C - 1250)$$
(8.4)

According to these equations, the minimum pressure to form the Ca-Tschermak's molecule in clinopyroxene is 11.5 kbar (T = 1160°C). According to Irving (1974), pyroxenes with high CaAlAlSiO₆ contents are considered to form at high temperatures (> 1000°C) at 10 to 20 kbar pressure. Solubility of Al₂O₃ in pyroxene increases with increasing pressure according to the reaction:

$$CaMgSi_2O_6 + xCaAl_2Si_2O_8 = CaMgSi_2O_6 * xCaAl_2SiO_6 + xSiO_2$$
(8.5)

The molar volume of the right hand assemblage is less than the left-hand assemblage and the content of $CaAl_2SiO_6$ would therfore be expected to increase with pressure at a given temperature (Deer *et al.*, 1978).

The small amount of plagioclase in the xenolith, together with the high content of pyrope end-member in garnet, suggest that the xenolith equilibrated in the high-pressure granulite facies, close to the transition beween the granulite and eclogite facies.

8.4 The Garnet-Clinopyroxene Fe-Mg Exchange Thermometer

This thermometer has been studied by many authors (Ellis and Green, 1979; Saxena, 1979; Ganguly, 1979; Powell and Holland, 1985, 1988; Krogh, 1988; Pattison and Newton, 1989). It is based on the Ca and Fe/Mg contents of coexisting garnet and clinopyroxene. The approach of Ellis and Green (1979) and Krogh (1988) were used here. Pattison and Newton (1989) method was not used because Mg-rich rocks have poor resolution on their graphs, and also because their study is based on garnet and pyroxene poor in ferric iron. Ellis and Green (1979) have derived the following empirical expression:

$$T(K) = \frac{3102 X_{Ca}^{Gt} + 3030 + 10.86 P(kb)}{Ln K_{D} + 1.9034}$$
(8.6)

where X_{Ca}^{Gt} is the mole fraction of Ca in the garnet (Ca/Ca + Mg + Fe) and K_D is the distribution coefficient if the minerals are ideal solid solutions, expressed as:

$$K_{\rm D} = \frac{(X_{\rm Fe}^{\rm Gt})(X_{\rm Mg}^{\rm Cpx})}{(X_{\rm Mg}^{\rm Cp})(X_{\rm Fe}^{\rm Cpx})} \text{ or } \frac{({\rm Fe}^{2+})_{\rm Gt}}{({\rm Mg}^{2+})_{\rm Gt}} \cdot \frac{({\rm Mg}^{2+})_{\rm Cpx}}{({\rm Fe}^{2+})_{\rm Cpx}}$$
(8.7)

 X_{Fe}^{Gt} is the mole fraction of Fe²⁺ in the three equivalent divalent sites in the garnet structure and X_{Fe}^{Cpx} is the mole fraction of Fe²⁺ in the clinopyroxene, etc. (Ellis and Green, 1979). Krogh (1988) revised the expression to:

$$T(K) = \frac{-6173 (X_{Ca}^{Gt})^2 + 6731 X_{Ca}^{Gt} + 1879 + 10 P(kb)}{Ln K_D + 1.393}$$
(8.8)

These equations require a knowledge of the Fe^{2+} contents of the garnets and clinopyroxenes. In microprobe analyses, only total Fe is determined, and the Fe^{2+}/Fe^{3+} ratio has to be calculated. Pyroxenes were recalculated on a basis of six oxygen and four cations and Fe^{2+}/Fe^{3+} ratios adjusted by charge balance. Cations were distributed in the tetrahedral site and in the M1 and M2 sites according to Morimoto's (1988) approach. Garnets were recalculated on a basis of 24 anions and 16 cations according to Deer et al. 's (1978) method and Fe^{2+}/Fe^{3+} ratio adjusted by charge balance and stoichiometry. The composition of pyroxenes and garnets are given in Section 6.6. The ratios $(Fe^{2+}/Mg)_{Gt}$ and $(Fe^{2+}/Mg)_{Cox}$ were calculated for each of the garnet-pyroxenes pairs (PY2-G3, PY3-G4 and PY4-G5, Table 8.1). The other pyroxene and garnet analyses were averaged and then the ratios were calculated (analyses were from non-adjacent garnet-pyroxene, but because both minerals are highly homogenous through the xenolith, the analyses were not discarded). The sample PY7 was rejected because of a low total. The ratios were then averaged and the K_D value was calculated. To examine the effect of uncertainty in ferric iron content on calculated temperatures, K_D values were calculated with and without, respectively, a recalculation for Fe³⁺ content. In the latter case, the whole iron content of the mineral is expressed as Fe^{2+} and the calculations based on these values have the subscript "Fetotal". The results are presented in Table 8.1. Using equations 8.7 and 8.8, and values obtained in Table 8.1, the temperature for a minimum pressure of 12 kb and a maximum pressure of 25 kb were calculated (Table 8.2) for the three garnet-pyroxene pairs. The results are shown graphically on Figure 8.1. As can be seen, the temperature calculated appears to be significantly higher when the iron content of both pyroxenes and garnets is assumed to be Fe^{2+} , which is unrealistic. The effect of analytical errors is to increase the Fe³⁺ content and thus move the curves to the left with respect to the temperatures obtained when $Fe_{total} = Fe^{2+}$. Thus, the series of curves to the left (with Fe^{3+}) represent minimum temperatures of equilibration.

	G3	G4	G5	Gl	G2	G6	G7a	G7b	Average Garnets
Fe ²⁺ /Mg	0.439	0.418	0.427	0.412	0.436	0.403	0.364	0.385	0.399
Fe _{total} /Mg	0.530	0.522	0.529	0.517	0.522	0.532	0.503	0.507	0.516
$X_{Ca(Fe}^{2+})$	0.216	0.226	0.209	0.213	0.206	0.210	0.193	0.194	0.203
$X_{Ca(Fe total)}$	0.206	0.214	0.198	0.202	0.197	0.196	0.178	0.181	0.191
							•		
	PY2	PY3	PY4	Р5	PY5				Average Pyroxenes
Fe ²⁺ /Mg	0.095	0.092	0.097	0.074	0.136				0.105
Fe _{total} /Mg	0.249	0.251	0.242	0.245	0.253				0.249
$K_{\rm D} ({\rm Fe}^{2+})$	4.609	4.538	4.408						3.805
ln K _D (Fe ²⁺)	1.528	1.512	1.484						1.336
K _D (Fe _{total})	2.134	2.079	2.184						2.069
In K _D (Fe _{total})	0.758	0.732	0.781						0.727

Table 8.1: Calculation of the distribution coefficient K_D for three garnet-pyroxene pairs. The coefficient was also calculated for an average of five garnets and two pyroxenes $[X_{Ca(Fe}^{2+}) = Ca/(Ca + Mg + Fe^{2+}); X_{Ca(Fe total)} = Ca/(Ca + Mg + Fe_{total})].$

	12 kbar	12 kbar	25 kbar	25 kbar
	$Fe = Fe^{2+}$	$Fe = Fe_{total}$	$Fe = Fe^{2+}$	$Fe = Fe_{total}$
Ellis and Green	844-857	1133-1178	885-899	1185-1232
Krogh	811-831	1148-1213	856-875	1208-1275

Table 8.2: Temperature of equilibration (°C) for the three garnet-pyroxene pairs at 12 and 25 kbar.



Figure 8.1: Equilibration temperature ranges for the garnets and pyroxenes from the granulite xenolith calculated with Ellis and Green (1979) and Krogh (1988) garnet-clinopyroxene geothermometers. The reaction boundaries garnet-in and plagioclase-out are from Spear (1993). The dashed lines are for the olivine tholeiite composition and the double dashed lines are for the quartz tholeiite composition. The low temperature series of curves are results for which Fe³⁺ has been estimated from stoichiometry. The high temperature series of curves were obtained when the whole iron content in garnets and pyroxenes is assumed to be Fe²⁺.

8.5 Single Pyroxene Thermometry

Lindsley (1983) calibrated thermometers based on the equilibria of quadrilateral pyroxenes for pressure of leatm and 5, 10, and 15 kbar. An estimate of the minimum temperature of crystallization of a single pyroxene can be obtained using his thermometers, since at or below the temperature of saturation a second pyroxene would have formed (Lindsley, 1983). Pyroxenes from the granulite xenolith were recalculated in terms of Wo, En and Fs following Lindsley's (1983) scheme (En = 0.36, Wo = 0.34, Ca-Ts = 0.15, Fs = 0.03, Ac = 0.06, and Jd = 0.05 mole %), and were plotted on the thermometer at 15 kbar. They fall on the 1200°C isotherm. This temperature is significantly higher than the one obtained using the Fe-Mg exchange garnet-clinopyroxene thermometer. Lindsley (1983) observed that pyroxenes with high alumina content yield apparent high temperatures. Accordingly, the thermometer should be restricted to pyroxenes containing more than 90% Wo + En + Fs (less than 10% Tschermak's component). Removal of the Tschermak's component from the pyroxene before plotting on the Di-Hd-En-Fs thermometer results in underestimation of the activity of Wo and yields an apparent high temperature. The garnet pyroxenite has over 8 wt.% Al₂O₃ which is the limit for utilization of the thermometer. If Davidson and Lindsley's (1985) thermometer is used, the pyroxene composition yields a temperature of $\sim 1050^{\circ}$ C at 15 kbar. This temperature seems more realistic, considering that the aluminum is mainly present as Ca-Ts component in the granulite pyroxenes and that this component is stable in high temperature, moderate pressure conditions (Smith, 1988). As the temperature decreases, the molecule is not stable and often exsolves from the pyroxenes.

8.6 Conclusions

Based on the proportions and compositions of plagioclase, garnet and pyroxene in the granulite xenolith as well as experimental work done by several authors on rocks of similar composition, it seems that the xenolith equilibrated at a pressure of around 15 kbars. The minimum temperature of equilibration using two Fe-Mg exchange thermometers is around 850°C. The temperature obtained is highly sensitive to the Fe^{3+}/Fe^{2+} ratio in pyroxenes and garnets. As this ratio has been calculated and not measured, its precision depends upon the quality of the microanalyses used in its calculation. If all the iron is assumed to be ferrous in garnets and pyroxenes, the temperature obtained is around 1150 to 1200°C. The high Ca-Tschermak's content of the pyroxenes (15 mol %) and the low jadeite content also suggest that the pyroxenes equilibrated at high temperature (> 1160°C which is the minimum temperature at 11.5 kbar to form Ca-Tschermak, or 1200°C at 15 kbars) and moderate pressure.

9. MODE OF OCCURRENCE OF SAPPHIRES IN THE DIKE

9.1 Introduction

Dahy (1991) suggested that the Yogo magma partially melted and desilicated a pelitic schist at the base of the crust or at a higher level, producing a plagioclase-pyroxene-corundum rock. He also suggested that the corundum was formed during metamorphism of bauxite-rich Precambrian sediment. Assimilation of the basement metamorphic complex by the Yogo magma consumed the silicate minerals but left the corundum mostly intact (Dahy, 1988). His other hypothesis was that the corundum crystallized directly from the silica-deficient alumina-rich magma.

Clabaugh (1952) was of the opinion that the Yogo sapphires crystallized directly from the magma as sapphires have not been found in inclusions of older rocks within the dike. He also mentioned that the crystal form of the sapphires, their lack of twinning and parting, is unlike that of corundum formed in a metamorphic environment. His other argument against the sapphires as xenocrysts is the fact that nearby intrusions are barren of sapphires. Another theory advanced by Clabaugh (1952) has a relatively small body of silica-deficient magma invading a zone of shattered kyanite-bearing gneiss in pre-Belt rocks at considerable depth below the surface. He proposed the following equations:

$$2Al_2SiO_5 + 2SiO_2 + 2NaAlSiO_4 + CaMgSi_2O_6 \Rightarrow MgAl_2O_4 + 2NaAlS_3O_8 + CaAl_2Si_2O_8 (9.1)$$

kyanite + quartz + nepheline + diopside \Rightarrow spinel + plagioclase

and:

$$Al_2SiO_5 + SiO_2 + NaAlSiO_4 \Rightarrow Al_2O_3 + NaAlS_3O_8$$
(9.2)

kyanite + quartz + nepheline \Rightarrow corundum + albite

According to Clabaugh (1952), reactions between the silica-deficient magma and other minerals may also account for the corundum. For example, muscovite from gneisses and schists could have reacted with the Yogo magma to produce corundum, spinel, and orthoclase or leucite.

9.2 Phenocrysts or Xenocrysts?

The evidence suggesting that the sapphires are phenocrysts includes the morphology of the sapphires, their lack of twinning and parting, their unusual clarity and lack of inclusions, which suggests high temperatures and pressures of formation.

The evidence for xenocrystic sapphires begins with the fact that Dahy (1988) found a plagioclase-diopsidecorundum xenolith. Also noteworthy is the high degree of corrosion of the sapphires and the sudden change in the Al-content of most minerals analyzed. The pyroxenes, phlogopite, and magnetite crystals all have rims that are Al-rich compared to their cores.

This author has suggested that the pleonaste spinel formed by the pyrometamorphic reaction of Al-rich minerals (Al-rich pyroxene, phlogopite), and noted the presence of pleonaste on phlogopite and in the matrix. This suggests that at one time in the history of the Yogo dike, highly aluminous material was assimilated in the magma. Although very few corundum-bearing xenoliths have been found, this hypothesis seems to be the most probable. If corundum was incorporated in the magma at a great depth, the high temperature of the ultramafic magma, together with the rapid ascent of the magma to the surface would contribute to the disintegration of the corundum-bearing xenoliths. Diamonds are a good example of this

process. They are highly corroded, and are rarely found in the xenoliths in which they formed (eclogite and peridotite).

10. CHARACTERISTICS OF YOGO SAPPHIRES

10.1 Comparison With Other Occurrences

Yogo sapphires have unique and outstanding characteristics. While sapphires worldwide are usually silky, zoned and heavily included, the majority of Yogo sapphires are free of inclusions and are unzoned. A high proportion of the stones have a "cornflower blue" colour, which is the most desirable colour for a sapphire. A unique characteristic of the Yogo is its brilliance, even under artificial light.

The morphology of the Yogo sapphire is also very unique. Morphology and crystallography of the Yogo sapphires have been described in great detail by Pratt (1897) and also by Clabaugh (1952). Crystals are platy with the c axis perpendicular to the largest face. Ruby crystals often show this habit, but it is very uncommon in sapphires (Hughes, 1990). All the sapphires observed were etched with triangular depressions and also triangular areas of positive relief.

The Yogo sapphire crystals are small. Only a dozen stones exceeding 5 carats (1 carat = 0.2 g) are found per year, and these usually do not exceed 8 carats. Between half and two-thirds of the weight is lost during the cutting process, so these rough stones will yield finished gemstones between 1.6 and 4 carats in weight. The bulk of the production is cut in melee (stones less than 3 mm in diameter).

The largest Yogo sapphire ever found was a 19 carat stone (rough), mined about 1910. The second largest stone, weighing 14 carats, was found in 1992 at the American Mine, a few weeks before our visit.

Due to their excellent colour and clarity, Yogo sapphires command very high prices. A cut Yogo with a cornflower blue colour sells for between US\$2,000 and US\$4,000 per carat for stones over 1 carat.

There are very few chemical analyses of sapphires published in the literature, and so it is difficult to compare the composition of theYogo sapphires with those from other localities. As shown in Chapter 6.5, Australian sapphires are usually higher in iron than the Yogo material. The Ti content is similar, although more accurate analyses of trace elements would be needed (at ppm level) to make a proper comparison. Sri Lankan sapphires are poorer in iron than the Yogo stones, although their hue (intensity of colouration) is usually similar to that of the Yogo material.

Voynick (1985) suggested that the absence of inclusions, the zonation in the Yogo sapphires, and their uniform colour, are due to a lengthy period of crystallization at great depth and at high temperatures and pressures. This way, each slowly developing crystal could literally purge itself of foreign minerals, rather than trapping them within. Dahy (1988) proposed that the sapphires were naturally heat treated when they were picked up by the ascending lamprophyric magma, and that their great clarity is due to this effect. The majority of sapphires (from Australia, Cambodia, Thailand, and China) are derived from alkali basalts, and many gemmologists believe that the sapphires are xenocrysts in the magma. This means that these sapphires have also been heat treated, although they contain numerous inclusions and silk, and are often green in colour. The main factor here is probably not the temperature of heating of the sapphires (the lamprophyric magma was probably only slightly hotter than the alkali basalt magma) but the time the sapphires spent in the magma and the oxygen fugacity of the melt. Resorption is not due to melting (as the melting point of pure corundum is 2052°C) but solid state chemical reactions (Emmett and Douthit, 1993) which are effective between 1300°C and 1900°C. Resorption and etching of the crystals suggests that they were created before solidification of the magma or that they were in disequilibrium with the magma due to changes in pressure or due to magma mixing or contamination.

10.2.1 Introduction

Ninety percent of the world's mine production of rubies and sapphires, whether from Thailand, Ceylon or Australia, is cut in Bangkok, then sold by Thai dealers to gem merchants around the world.

In the 1970's the booming demand for fine blue sapphires (outpacing the supply) led the Thais to experiment on heat treatment of *geuda* from Sri Lanka (Ceylon). These *geuda* are milky white in colour and were considered worthless on the gemstone market. A large proportion of the Sri Lankan sapphire production is in the form of *geuda*. When the Thais discovered that some of the *geuda* would turn into lovely marketable blue sapphires after heating, they bought all the material they could put their hands on. The Sri Lankans were at first delighted to unload their worthless *geuda* on the Thais, but soon realized what was happening and raised the priced of *geuda* to almost that of rough blue sapphires. These sapphires, often referred to as "cooked", "burned", or "fried" stones, that first started as worthless *geuda* were now sold at almost, if not the same price as natural blue sapphire, without disclosure to the public. This issue of whether or not treated gems should be sold without disclosure is currently an item of hot debate in trade circles (Hughes, 1990).

Their success with *geuda* led the Thais to experiment with other sources of off-colour sapphires, such as the greenish-blue and dark Australian material. By 1980, *about 95 percent* of all the sapphires on the market had been heated, both those on the retail counters and those in the enormous gem inventories of American gem merchants (Mumme, 1988).

The Yogo sapphire is the only sapphire in the world that is not heat treated. Its natural colour is already ideal. At the beginning of the 1980's, Intergem (see Appendix A) began advertising the Yogo sapphires as *Guaranteed Untreated* blue sapphires.

10.2.2 Heat Treatment Techniques

The heat treatment of rubies and sapphires has been practised for many centuries, possibly dating back to Roman times (Hughes, 1990). However, only gem quality material was used and the heat treatment was employed to improve the colour and clarity of the stones.

The Thais heat treat sapphires in a very simple way. The stones are mixed with coke to produce a reducing atmosphere and they are put in a primitive furnace (often a 45 gallon oil drum) and heated. Some of the stones gain a favorable colour, some do not, and some crack or are destroyed. The yield of such a rudimentary process is quite low.

Emmett and Douthit (1993) conducted some experiments on heat treatment of Rock Creek sapphires. They showed that the most important factor influencing the colour and clarity of the heat treated stone is not the temperature but the atmosphere to which the stones are exposed. Low oxygen partial pressures favour the reduction of impurity ions, such as the partial reduction of Fe^{3+} to Fe^{2+} . High partial pressures drive the reaction in the other direction, that is, Fe^{2+} to Fe^{3+} . Emmett and Douthit (1993) also found that the hydrogen partial pressure is as important as the oxygen partial pressure; in fact reduction will not proceed without hydrogen regardless of the oxygen partial pressure. Temperature and time are also important, but not as important as the oxygen partial pressures. Heat treatment at high temperature (1800° C) for 10 to 20 hours partially heals fractures. Rutile is one of the most common inclusions in sapphires. Although it has a melting point of 1830°C, heat treatment at 1600°C will dissolve rutile needles 1 to 5

microns in diameter (Emmett and Douthit, 1993). This is possible because of the high diffusion rate of Ti^{4+} . Most natural sapphires are not blue since neither Fe^{3+} nor Ti^{4+} are easily incorporated into sapphire (Emmett and Douthit, 1993). The solubility of Ti^{4+} in sapphire is so low at normal temperatures that the majority of the Ti^{4+} in natural sapphires is exsolved as titanium-bearing microcrystals (Emmett and Douthit, 1993). Under certain conditions, Fe^{2+} and Ti^{4+} can enter sapphire at the same time and their solubility together is greater than the solubility of either alone (Emmett and Douthit, 1993). This is due to mutual charge compensation; that is, one Ti^{4+} ion plus one Fe^{2+} ion have a total charge of +6, which is equal that of the two Al^{3+} ions they replace. In a simplified way, the heat treatment recipe to convert pale green, Rock Creek sapphires into blue stones is as follows: the stones are first heated in either an oxidizing or a neutral atmosphere to dissolve the rutile, and they are then heated in a reducing atmosphere to reduce some of the Fe^{3+} to Fe^{2+} . (Emmett and Douthit, 1993). Heat treatment is conducted for 1 to 10 hours. Pale green, pale blue, and near colourless stones can also be heat treated at 1650° C in a reducing atmosphere that contains some hydrogen.

11. CONCLUSIONS

The Yogo dike is Eocene in age (48 ± 1.3 Ma) and is classified as an ouachitite of the ultramafic lamprophyre group. The rock has a chemistry indicating its ultramafic character and its association with carbonatites. The geochemistry of the rock compared to the geochemistry of the Yogo Peak intrusion indicates that the two intrusions are not petrogenetically related, as was proposed by some authors. Sapphires occurring in the dike are probably xenocrystic in origin. The arguments in favor of this conclusion are the following: (1) crystals are highly resorbed and are always rimmed by pleonaste spinel, which indicates a disequilibrium reaction between the magma and the sapphires; (2) the Yogo magma is not corundum normative; (3) sapphire-bearing xenoliths have been found during previous studies (Dahy, 1988, 1991), notably a sapphire-pyroxene-plagioclase xenolith and a sapphire-bearing diopside-phlogopite autolith; (4) some inclusions found in the sapphires (sphalerite, kyanite? rutile?) are not compatible with the paragenesis of the Yogo dike rock; (5) the presence of Mg-rich pleoanaste spinel as inclusions in some phlogopite and pyroxene grains and as discrete grains in the matrix is an important feature related to the presence of sapphire in the rock. This type of spinel is often found with sapphires and is usually the result of moderate to high temperature metamorphism of Al-rich phases. Pleonaste spinel is thought to have originated by mixing of Al-rich material with the Yogo magma. The Al-rich rims of pyroxenes and phlogopites as well as the Al-rich composition of the last minerals to crystallize (magnetite, analcime) also supports this theory.

The third point should be enough to prove the xenocrystic nature of the sapphires, but only two sapphirebearing xenoliths have been found (Dahy, 1988, 1991) and the sapphires were identified using optical techniques. During the course of this study, many crystals from xenoliths were found to be optically similar to sapphires, but were identified as Al-rich pyroxenes using EDS analyses. One autolith (diopsidephlogopite) was found partially englobing a sapphire. This autolith should be studied in more detail to

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determine whether the sapphire is in the autolith or if it is in an embayment. The autoliths are though to be cumulate phases of the magma chamber as the clinopyroxenes and the phlogopites have a composition similar to the most primitive megacrysts found in the rock. Thus, if the sapphire belongs to the autolith, it comes from a great depth and would logically be a phenocryst in the cumulate phase.

The depth at which the Yogo magma originated is uncertain. Some authors have suggested a minimum depth of 100 km. Xenoliths on which geothermobarometry can be applied are rare in the dike. Geothermobarometry on a garnet-cinopyroxene-plagioclase granulite xenolith yielded pressures in the range of 12 to 20 kbar, and a temperature of around 850°C. This suggests that the xenolith was picked up by the magma at a depth between 40 and 70 km.

A detailed study of the trace elements present in the sapphires (at a ppm level) would help constrain their origin. It would be interesting to study the stable isotopes of oxygen in sapphires as these could give some indications as to the provenance of the oxygen. Oxygen isotopes could also be used on the carbonates of the ocelli to determine whether the carbonates are primary or secondary. More fluid inclusion work should also be done. A study of the composition of the melt inclusions present in a few sapphires would give information on the composition of the fluid in which the sapphires grew.

Most of the sapphires on the market come from alkali basalt. These sapphires are thought to be xenocryts in the rock. The unusual clarity of the Yogo sapphires compared to most others cannot be accounted for by natural heat treatment of the sapphires by the hot Yogo magma, since sapphires from alkali basalts probably undergo a similar treatment. Original composition of the crystals or depth of formation of the sapphires might be other factors contributing to their high clarity. The latter is probably a major factor. This statement is supported by the fact that none of the numerous lamprophyre intrusions located in the area of the Yogo dike are sapphire-bearing. The Yogo dike is the only ultramafic lamprophyre and is likely to come from greater depth than the alkaline and calc-alkaline lamprophyres found in the vicinity.

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APPENDIX A

A HISTORY OF SAPPHIRE MINING AT THE YOGO LOCALITY

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A. A HISTORY OF SAPPHIRE MINING AT THE YOGO LOCALITY

A.1 Introduction: Gemstone Exploration in North America

Although gemstones mining has been conducted for centuries (even millennia) in such countries as Columbia, India, and Sri Lanka, it has a very young history in the northern hemisphere. In Canada, to date, there are no mines exploiting precious gemstones (emerald, sapphire, ruby and diamond) and only a few small mines extracting semi-precious stones such as quartz, garnet, jade, rhodonite, and labradorite.

When the Spanish first put foot on the North American continent, their goal was to bring back gold and gemstones to Spain. They were not as fortunate as they were in South America where they found (or stole) gold, emeralds, amethyst and turquoise in abundance. In the 1600's the English also failed to find gold and significant amounts of gem material. For the next few centuries very little exploration was conducted for gemstones. Gold, silver and base metals were the main targets.

It is easy to understand why gold and, to some extent, silver, attracted prospectors so much more than gemstones. Even raw gold has a fixed universal value that does not depend upon appraisals by gemologists, mineralogists or jewelers, nor upon the intricacies of cutting and polishing. Because gold has a fixed value per unit weight, it is easy for a prospector to evaluate the market value of a given amount. Gold is also easy to identify; only a few minerals look like it (pyrite, chalcopyrite) and an experienced prospector can easily tell them apart. It takes considerably more expertise to identify rough gemstones. The matter is further complicated by the fact that their values are derived not only from their weight but also from their size, origin, colour, clarity and cut. There are no fixed prices for different grades of most gemstones (unlike diamonds, whose prices are controlled by De Beers or the Central Selling Organization in London). Another major problem with gemstone exploration in North America was the lack expertise in the area of gemstone identification. Few mineralogists were gemstone connoisseurs and few gemologists could identify an uncut mineral. One of the few authorities was Dr. George Frederick Kunz, who worked for Tiffany and Company of NewYork around the turn of the century. Dr. Kunz, a gemologist, mineral collector, and scientist, was also an advocate for American gemstones.

Today, exploration for gemstones in North America is mainly conducted on a very small scale by amateur prospectors. The discovery of diamonds in the Canadian North may change this situation.

A.2 Missouri River Sapphires

Although corundum has been produced from North Carolina since the beginning of the 1800's, it was not until the end of that century that gem quality material was found in the United States. In 1865 sapphires were discovered in Montana in placer gold mining operations along the Missouri River (Voynick, 1985). The first large scale mining was conducted by the Sapphire and Ruby Company of Montana Limited in 1891. However, the operation was unsuccessful because few of the stones had a good blue colour. The deposits were sporadically mined for industrial grade corundum until the introduction of cheap, easily produced synthetic material in the 1900's.

A.3 Yogo Sapphires

The following history of the Yogo deposit is based largely on Voynick (1985).

In 1876, a gold rush began on one of the last unexplored streams in Montana, the Yogo Creek. A boom town named Yogo City soon developed. Little gold was found in the creek, and after three years, the town

was deserted. Prospectors exploring the lower section of the creek (about three miles downstream of Yogo City) found some blue translucent pebbles which they discarded. Two small gold mines opened near Yogo City in 1894; this attracted the attention of J. Hoover, a local prospector. He looked at the lower part of Yogo Creek and also found some small translucent blue pebbles.

A year later Hoover and his two partners, S.S Hobson and J. Bouvet, were operating a small placer gold operation on Yogo Creek. During the summer Hoover collected enough of the blue pebbles to fill a cigar box. It is unclear how the sapphires were identified. One version of the story says that Hoover gave the cigar box to a friend in Great Falls who had them identified. Another version says that Hoover sent the pebbles to Tiffany and Company for identification. Whatever version is true, the sapphires ended up on the desk of Dr. Kunz, who identified and appraised them. Along with a letter from Tiffany and Company declaring the stones to be "sapphires of unusual quality", Hoover and his associates unexpectedly received a check for \$3750. This arrived after an unsuccessful season that yielded only \$700 worth of gold. Not surprisingly, the three partners quickly started mining sapphires. Most of the material they recovered was pale to cornflower blue. Furthermore, a high percentage of the stones were clean, without zoning or inclusions. However, there were problems with the Yogo sapphires which remain to this day. The main one is size, in that the bulk of the material consists of small (<1 carat) flat (<2 to 2.5 mm) crystals from which only melee stones (1 to 3 mm) can be cut. Rough stones of three carats or more that yield cut stones of more than one carat are rare.

In February 1896 Jim Ettien, a local shepherd, discovered a "vein" containing blue pebbles east of Yogo Creek. Knowing of the discovery by Hoover and associates of sapphires on Yogo Creek, it was easy for Ettien to deduce that his blue pebbles were sapphires and that they were of considerable value. Later that year, Hoover and his partners found more of the "vein" (from Ettien's claims west to Yogo Creek) and filed eight lode claims on the extension.

By the end of the summer of 1896, many thousands of carats of rough sapphires had been recovered. In the fall Jim Ettien sold his claims to Hoover and associates for \$2,450. The latter now controlled about 2.5 miles of the dike, or most of its known length.

In an 1897 issue of the American Journal of Science, Dr. Kunz compared the Yogo sapphires to those found earlier in Montana (Kunz, 1897):

"As to the value of the early Montana sapphires in jewelry, it is hardly possible to predict how far it may really be important. Much beautiful material has already been obtained, but little of high value. Those from the Missouri bars had a wide range of color, light blue, blue-green, green and pink, of great delicacy and brilliancy, but not the deep shades of blue and red that are in demand for fine jewelry. As semiprecious, or "fancy" stones, they have value, however.

The Yogo Gulch-Judith River region is more promising, the colors varying from light blue to quite dark blue, including some of the true "cornflower" blue tint so much prized in the sapphires of Ceylon. Others incline to amethystine and almost ruby shades. Some of them are "peacock blue" and some dichroic, showing a deeper tint in one direction than in another; and some of the "cornflower" gems are equal to any of the Ceylonese, which they strongly resemble, more than they do those of Cashmere. Several thousand carats were taken out in 1895 (1896 in Voynick, 1985), from a preliminary washing of 100 loads of the "earth"; of these, two hundred carats were of gem quality and yielded, when cut, sixty carats of fine stones worth from \$2 to \$15 per carat. All, however, are small, none having yet been obtained of more than 1 1/2 carats in weight."

Also in 1897, following the death of Bouvet, Hoover's original partnership was reconstituted as the New Mine Sapphire Syndicate with two new members, M. Dunn and G.A. Wells. The partners began looking for new capital and a market for cut stones. When the gem merchants in New York showed little interest Wells sailed to London and met with the firm of Johnson, Walker and Tolhurst Limited. They had recently acquired significant mining interests in Ceylon and Burma, with the idea of acquiring enough of the world's sapphires to control the market, like De Beers had done with diamonds. Johnson, Walker and Tolhurst Limited quickly agreed to a ten-year contract as the sole marketing agent for Yogo sapphires.

In 1897 Hoover sold his quarter-interest in the New Mine Sapphire Syndicate for \$5,000. In August of the same year the same quarter-interest was sold to Johnson, Walker and Tolhurst Limited for \$100,000!

In 1899 a small steam plant was constructed to power the pumps for hydraulic mining of the weathered upper section of the dike. The mud that resulted from washing was processed in sluice boxes. The 1899 production was 400,000 carats of sapphires, 125,000 of which were of gem quality. The rough stones were sent to London for sorting and cutting. The stones too small or too flat for cutting were sold as mechanical jewel bearings or abrasives. The year's production was worth \$70,000.

Although marketing of the Yogo sapphires seemed encouraging, Dunn sold his share of the mine to the British in 1899, followed by Hobson (the last American shareholder) in 1901. In 1900 Yogo sapphires were exhibited at the Universal Exposition in Paris. In direct competition with oriental sapphires, they were awarded the silver medal. Despite this, many retail jewelers in Europe were misrepresenting the larger Yogo gems as oriental sapphires, since few consumers new about the new source.

In 1899, C.T. Gadsden began working as general assistant at the Yogo mine, commonly called the English Mine. In 1902, he was named resident supervisor. According to Voynick (1985), "Gadsden would become the very essence and soul of the English Mine. For the next half century, Yogo would be the private little empire of Charles T. Gadsden".

In 1896, J. Burke and P. Sweeney found an extension of the dike west of Yogo Creek in Kelly Coulee. They filed six lode claims on July 4, 1896, and named their property the "Fourth of July Claim" (this claim is west of the American Mine; however, the "Fourth of July Claim" is presently located just east of the American Mine). Burke and Sweeney began mining two years later but were plagued by financial and technical difficulties. In 1904 they sold their property to the Yogo American Sapphire Company for \$100,000.

The period around 1910 brought the recovery of some of the largest Yogo sapphires on record. A 5 3/4 carat stone with a beautiful deep blue colour was found in September 1910 at the American Mine. In the same period, the English mine produced two stones of twelve and nineteen carats, respectively. The latter was the largest stone ever recovered from the dike and was approximately the size of a peach pit. In June, 1991, a 14 carat stone was found at the American Mine by employees of Roncor Incorporated.

Towards the end of 1913 the Yogo American Sapphire Company declared bankruptcy. In May of 1914 their property was acquired by the New Mine Sapphire Syndicate. Gadsden now had control of the entire length of the Yogo dike. However, by the end of the war the Syndicate was facing serious problems. The demand in Europe was for large sapphires and few were being found. The company was also paying taxes amounting to 50.5% of gross profits. Furthermore, there was concern that the newly introduced synthetic corundum would drastically reduce the sales of natural stones. The Verneuil process was invented by A. Verneuil, a French chemist, in the late 1800's. By 1903 laboratories were producing six million carats of synthetic sapphires annually. By 1920, the Verneuil process was producing high quality synthetic sapphires at a fraction of the cost of top grade natural material. The inclusion free and unzoned Yogo sapphires were threatened by these cheap synthetic sapphire that could look as spectacular at a fraction of the price.

In 1922, after more then twenty years of operation, the British decided to sell the Yogo dike. The property was put up for sale for \$150,000. However, on July 26, 1923, a cloudburst destroyed most of the mining

equipment. By 1929 the production was valued at a mere \$4,850. With no hope of sale the English Mine was officially closed. According to Clabaugh (1952):

"The English Mine production on the Yogo dike had amounted to well over 16 million carats, (or) three and one-half tons of sapphires valued in the rough at \$2.5 million. About 15 percent, (or) 2.5 million carats, were of gem quality. Assuming a conservative cutting retention of thirty percent, the English Mine had therefore provided the world gem markets with some 675,000 carats of fine, cut blue sapphires. With an average retail value of \$30 to \$40 per carat, the gem value of the Yogo sapphires had certainly exceeded \$25 million."

Clabaugh also wrote, after a visit to the English Mine in the summer of 1946, that:

"The geology of the Yogo sapphire deposit is exceedingly simple. A nearly vertical sapphire-bearing igneous dike cuts through gently dipping limestone" (Clabaugh, 1952).

The dike was not as simple as he claimed, as many people discovered after unsuccessful mining operations. Uneven grade, barren areas, grade dilution caused by limestone breccia in the dike (called "pre-dike" breccia in unpublished material from Delmer Brown, a gemologist who has studied the property), as well as limestone and dike breccia filling limestone cavities formed by fault movement after the intrusion of the dike (called "post-dike" breccia by Brown) were some of the problems to be faced when mining the dike. "post-dike" breccia were an important part of the dike in some areas (such as the American Mine). The grade in these sections was very low due to the high concentration of limestone fragments, especially when compared to the English Mine. After careful examination of fragments found in the dike, Brown has suggested that the intrusion could be as deep as 7,000 feet, based on the fact that it carries xenoliths of Precambrian rocks that are found at that depth in the stratigraphic sequence. Furthermore, xenoliths of all other formations below the Madison limestone can be found in the dike. Between 1929 and 1944 the mine was closed. The only activity was illegal digging by rockhounds. It is impossible to estimate how many large stones (five carats and up) were found during this period.

Sapphire International Corporation was the first company to work the mine since it was closed by the British. R. Kunisaki invested \$5 million into a 3000-foot tunnel that was driven eastward into the dike at the old American Mine site. Unfortunately, only small pockets of pure dike rock were encountered and Kunisaki declare bankruptcy in 1976.

In 1980, H. Bullock, D. Brown and J.R. Edington formed American Yogo Sapphire, Limited. Their plan was to mine and cut the Yogo sapphires but cost analysis revealed that the operation would only make a profit if they manufactured jewellery based on the Yogo gems. In 1983 the gem industry became aware of the controversial heat treatment of worthless *geuda* corundum from Sri Lanka. At that time, not even traditional heat treatment to enhance colours was disclosed to the consumer. Intergem (the new name of the company) capitalized on this in an ad campaign aimed at retail jewelers that encouraged them to "be exclusive dealers of the world's only guaranteed untreated sapphire". The gems would be sold with a "Certificate of Guarantee", that would state that "unlike most sapphires sold today, the Royal American Sapphire (Intergem's name for the Yogo gems) is not heat treated to improve its colour".

By 1983, over 200 retail jewelers were selling the Intergem product. However, the company was in financial trouble by 1986 and ownership of the mine reverted to Roncor Incorporated, previously Sapphire International Corporation. Roncor conducted small scale mining operations from 1987 to 1992, at the Middle Mine, located west of the old English Mine, and at Kelly Coulee. As of 1993 Roncor had signed a joint agreement with AMAX to study the feasibility of underground mining.

Remarks	J. Hoover finds blue pebbles in Yogo Creek.	Pebbles identified as sapphires by Tiffany and Company, New York.	Ettien discovers the dike and stakes two lode claims.	The partners file eight lode claims west of Ettien's, which they later buy for \$2,450.	Burke and Sweeney stake the "Fourth of July" claim which later becomes the American Mine.	With the death of Bouvet, Hoover and Hobson are joined by two new partners, M. Dunn and G.A. Wells.	Hoover sells his quarter- interest for \$5,000.
Property							
Value of Rough (\$)		3750					
Value of Cut Stones (\$/ct)		2 to 15 ^d 5 to 25 ^e		2 to 15 ^d			
Cut Stones (carats)		60 ⁴		60 ^d			
Gem Quality Sapphires (carats)		200 ⁴		200 ⁴			
Total Annual Production (carats)		A few thousand carats ^a		A few thousand carats			
Owner		J. Hoover, S.S. Hobson, J. Bouvet	J. Ettien	Hoover, Hobson, Bouvet	J. Burke, P. Sweeney	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate
Ycar	1894	1895	1896	1896	1896	1897	1897

Table A.1: Summary of the Yogo Gulch mining history.

Remarks	Johnson, Walker and Tolhurst Limited buy a quarter-interest for \$100,000. ^b		C.T. Gadsden becomes general assistant at the mine; implementation of hydraulic washing.	Excavation of a 30 m shaft.		The syndicate obtains a lease on the "Fourth of July" claim. ^c	
Property	English Mine		English Mine	English Mine		Kelly Coulce	
Value of Rough (\$)			70,000, 55,000 ⁶	80,000			
Value of Cut Stones (\$/ct)							
Cut Stones (carats)							
Gem Quality Sapphires (carats)		128,914ª	125,000	125,000	100,000 to 150,000ª		
Total Annual Production (carats)		425,776 ^ª	400,000	400,000	5,000 ounces plus gem quality material		200,000*
Owner	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	American Gem Syndicate	New Mine Sapphire Syndicate
Year	1897	1898	1899	1900	1061	1061	1902

Remarks	Gadsden is named resident supervisor of the English Mine.	Mining of the "Fourth of July" claim begins.	60 m shaft and 180 m tunnel		Purchase of the "Fourth of July" property for \$100,000.	Building of a mill at the American Mine.
Property	English Mine	Kelly Coulce or American Mine	English Mine			American Mine
Value of Rough (\$)	100,000, 40,000 ^a			30,170, 11,570		
Value of Cut Stones (\$/ct)	20 to 25					
Cut Stones (carats)	14,000					
Gem Quality Sapphires (carats)	40,000 ^ª			38,529 ^ª		
Total Annual Production (carats)	1,040,000ª	A few thousand carats	400,000 to 1,000,000	847,000 ^å		
Owner	New Mine Sapphire Syndicate	Burke, Sweeney	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	American Sapphire Company	American Sapphire Company
Year	1903	1903	1901 to 1003	1904	1904	1904 to 1907

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Table A.I

rty Remarks	Mine Operations are suspended by a court injunction prohibiting dumping of tailings into the Judith River. The tailings were said to be detrimental to farming; Gadsden proved otherwise by growing vegetables on them.	n Bankruptcy	n Purchase of the American Mine for \$60,000.			Mine The shaft is extended an additional 30 m for a total of
Prope	English I	America Mine	America Mine			English l
Value of Rough (\$)				200,000		
Value of Cut Stones (\$/ct)						
Cut Stones (carats)				100,000		
Gem Quality Sapphires (carats)				70,000*	°000,000	°00,000
Total Annual Production (carats)				600,000	500,000 ^a	568,406 ^ª
Owner	New Mine Sapphire Syndicate	American Sapphire Company	Yogo American Sapphire Company	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Sundicate
Year	1906 to 1907	1909	1909	1910	1161	1912

Remarks	Purchase of the American Mine by the Syndicate. Gadsden rewashes the tailings and recovers \$80,000 worth of rough, enough to offset the purchase price.	Production minimal due to the war in Europe.			A severe cloudburst destroyed most of the mining equiment. ^f	
Property	American Mine			English Mine	English Mine	English Mine
Value of Rough (\$)	80,000		200,325	200,000, 500,000 ^f	40,000, 36,500, 4,145ª	25,000, 20,263, 5,566 ^ª
Value of Cut Stones (\$/ct)						
Cut Stones (carats)						
Gem Quality Sapphires (carats)					118,800ª	46,950 ^ª
Total Annual Production (carats)			309,196ª		340,546°	325,267ª
Owner	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate
Year	1914	1915 to 1920	1920	1921	1923	1924

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Remarks				The mine is closed; the only activity is illegal digging by	rockhounds.	Purchase of the property for \$60,000 plus acquisition of 145,000 of the 150,000 traceable British shares.	The Yogo Sapphire Mining Corporation is reorganized as the New Mine Sapphire Syndicate. No work is done on the property.
Property	English Mine	English Mine	English Mine			Yogo dike	Yogo dike
Value of Rough (\$)	29,138, 4,237	19,000, 3,498	4,638				
Value of Cut Stones (\$/ct)							
Cut Stones (carats)							
Gem Quality Sapphires (carats)	54,495ª	42,469ª	6,451ª				
Total Annual Production (carats)	266,308ª	222,364ª	89,686 ^ª				
Owner	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate			Yogo Sapphire Mining Corporation	New Mine Sapphire Syndicate
Year	1925	1926	1927	1929	to 1949	1956	1956 to 1958

Remarks	Siskon, Incorporated of Nevada is contracted to work the mine in return for a share of the profits. After a disasterous season the company files a breach of contract suit against the owners to recover \$54,960.	The property is left unguarded. Thousands of rockhounds visit the mine to dig for sapphires.	Siskon Incorporated purchases the dike for \$75,000 after the court rules in their favor.	The property is leased to a group led by A. Baron, a jeweler.
Property		Yogo dike		
Value of Rough (\$)				
Value of Cut Stones (\$/ct)				
Cut Stones (carats)				
Gem Quality Sapphires (carats)	4,000			
Total Annual Production (carats)	50,000			
Owner	New Mine Sapphire Syndicate	New Mine Sapphire Syndicate	Siskon, Incorporated	
Year	1958 to 1959	1959 to 1963	1965	1965 to 1968

Remarks	The property is sold to Sapphire Village Incorporated for \$585,000. They plan to subdivide part of the property into lots and sell them to rockhounds.	C. Kunisaki, one of the partners of Sapphire Village Incorporated, purchases the assets of the company.	A new company headed by V. di Suvero, who attempts to advertise and market the sapphires and raise capital.	H. Bullock, D. Brown, and J.R. Eddington form American Yogo Sapphire, Limited and purchase the mine for \$6,000,000.	\$1,600,000 in jewelery.	\$3,000,000 in jewelery.	
Property	Yogo dike	Yogo dike, American Mine	Yogo dike	Intergem Mine			
Value of Rough (\$)							
Value of Cut Stones (\$/ct)							
Cut Stones (carats)					2000		
Gem Quality Sapphires (carats)				40%			
Total Annual Production (carats)	Only a few thousand carats of rough recovered			750,000			
Owner	Sapphire Village, Incorporated	Sapphire International Corporation	Sapphire- Yogo Mines, Incorporated	American Yogo Sapphire, Limited	Intergem	Intergem	Intergem
Year	1968 to 1972	1973 to 1976	1977 to 1979	1980 to 1985	1983	1984	1985

Remarks	
Property	Middle Mine, Kelly Coulee
Value of Rough (\$)	
Value of Cut Stones (\$/ct)	
Cut Stones (carats)	
Gem Quality Sapphires (carats)	
Total Annual Production (carats)	
Owner	Roncor, Incorporated
Year	1987 to 1992

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Table A.1: (Yogo Gulch mining history) continued.

^aClabaugh (1952).

^b Bancroft (1984) wrote that British control was attained in 1901 and that "included in the sale were the following patented claims: Gold Cross, 4th of July, Klondike, Blue Diamond, Jewel, Snowdrift, Gem Survey, and the Hope and Dude placers". ⁶Wilson (1986) wrote that "no new mineral vein was discovered west of Jim Ettien's discovery until 1901". This was claimed by Hoover and partners in discovery was staked and recorded as the Lion lode and that it was purchased by the Yogo Lapidary Company, which operated the mine from 1904 to 1896 and the western extension, "Fourth of July" claim and the American Mine were claimed by Sweeney and Burke in 1896. Wilson wrote that the 1909. It was then acquired by the Yogo American Sapphire Company.

^dKunz (1897).

^eKunz (1896).

^f Baron (1982).

APPENDIX B

A REVIEW OF WORLD SAPPHIRE DEPOSITS

B. A REVIEW OF WORLD SAPPHIRE DEPOSITS

World sapphire occurrences are described in the following section (including Table B.1). Deposits in Australia, Sri Lanka and Thailand (the major producers) will be described first, followed by others in alphabetical order. The descriptions include geology of the deposit and sapphire habit, colour and physical characteristics when available.

B.1 Australia

Australia is an important producer of commercial grade sapphires. Corundum and sapphire are found in many parts of Australia; the major deposits are the New England fields in New South Wales and the Anakie fields in central Queensland. Smaller deposits are found in South Australia, Victoria and Western Australia.

Australian sapphires are usually dark to greenish blue, and they are often heat treated to eliminate the greenish overtone. Good quality Australian sapphires have not often been sold as such. This is because most of the Australian production was sold to gem merchants in Thailand, who often marketed the better stones as Thai or Burmese and the lower grade material as Australian (Newman, 1991). Recently, however, the Australian Jeweler's Association, the Australian Faceter's Guild and the Small Miner's Association have been working to eliminate Thai control of the sapphire industries of central Queensland and northern New South Wales (Newman, 1991).

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Table

Source	Ruby	Blue sapphire	Fancy sapphire ¹	Source	Ruby	Blue sapphire	Fancy sapphire1
Afghanistan	×			Myanmar (Burma)	×	x	×
Australia	×	major	major	Nepal	×		×
Brazil	×	×	×	Nigeria		×	×
Burundi		×		Pakistan	×	X	
Cambodia	×	×		Sri Lanka	×	major	major
China	×	×		Tanzania	×	X	major
Columbia		×	×	Thailand	major	major	major
India	×	×		USA	X	×	×
Kenya	×	×	×	Vietnam	×		
Malawi	×	×	×	Zaire		×	
Madagascar	X			Zimbabwe		x	x

x = source, major = major source.

 $^{\rm l}$ fancy sapphire includes yellow, pink, green, purple and orange stones.

B.1.1 The New England Fields

Sapphires were discovered in the Cudgegong and Macquarie Rivers in the New England district around 1850. Between 1919 and 1959 sapphires were sporadically mined by individuals and small companies, but prices for Australian sapphires were very low because they were considered inferior to the sapphires from Asian sources. After 1959, the prices increased due to exhaustion of traditional sources, and mining began on a large scale in the 1970's (Mumme, 1988).

The sapphires are usually found in alluvial deposits close to Tertiary basalt flows (Mumme, 1988). The sapphire-bearing gravel is generally composed of basalt pebbles, ironstones, fragments of porphyry, granite, metasediments, ilmenite, tourmaline, enstatite, pleonaste, and zircon (Mumme, 1988). Lishmund and Oakes (1983) have suggested that sapphires were brought to the surface by Tertiary pyroclastic rocks, basalts and diatremes. This theory is supported by the fact that the sapphires (assumed to be xenocrysts) are often rounded and corroded.

The sapphires recovered from the New England deposits often occur as flat hexagonal prisms, tapered hexagonal prisms, bipyramidal crystals, and as well rounded grains (Coenraads, 1992). The crystal faces often show corrosion features, and the crystals are often zoned. Stones most often range in size from 3 to 25 mm. Some flat hexagonal prisms 3 to 4 cm in diameter have been found, which indicates that some of the crystals grew to at least 12 cm in length (Coenraads, 1992).

The sapphires are predominantly dark blue, particoloured, or green; yellow stones are rare. The dichroism of these sapphires is strong, with the ordinary ray carrying the dark blue colour. Coenraads (1992) studied syngenetic mineral inclusions in New England sapphires and identified zircon, hercynite, gahnospinel, columbite, rutile, ilmenite, thorite, alkali and plagioclase feldspar, pyrrhotite, pyrochlore, horneblende,

mica, and primary iron-rich melt inclusions. Dating of the zircons yielded an age of 34.9 ± 1.4 million years. The presence of iron-rich mineral inlusions in New England sapphires suggest that they grew from a parent melt rich in Fe and poor in Si and Mg. The environment was rich in incompatible elements (e.g. U, Th, Nb, Ta, Zr) and alkalis (Na, K), which suggests that the sapphires are xenocrysts, since incompatible elements are concentrated in rocks more felsic than basalts (Coenraads, 1992).

About 20% of the material found is marketable, often between 1 and 40 carats. The remaining material is divided into very low quality sapphires (flawed, patchy colouration, small sizes), which constitute about 60% of the total material found, and into worthless opaque brown/green corundum (20%).

B.1.2 The Anakie Fields of Central Queensland

The Anakie sapphire mining district is located west of the central Queensland coast. It covers an area of approximately 900 km² (Mumme, 1988). The Anakie fields are believed to be the richest and most extensive sapphire fields in the world (Mumme, 1988). Sapphire mining in the Anakie fields occurs around the town of Anakie, at "The Willows", 40 km Southwest by road from Anakie, and at "Sapphire" and "Rubyvale" which lie 10 km and 16 km north of Anakie, respectively.

Sapphires were first identified as such in Retreat Creek, 21 km west-south-west of the Anakie township in 1873. Anakie produces mainly blue stones, but also fine-quality yellow and green stones. Other colours found include golden yellow, particoloured, colourless, and rarely alexandrite type (colour change) orange sapphires and rubies. Star sapphires are also found in the Anakie fields. Flawless, brilliant, evenly coloured and large golden yellow gems are characteristic of the "Willows" field. Sapphires at this locality occur in the river bed with red zircons and garnets. A few diamonds have also been found in the sapphire wash.

At the beginning of the century, from about 1900 to 1925, the finest blue stones from the Anakie gem field were purchased overseas by dealers who labeled them for resale as Kashmir or Burmese sapphires, while selling inferior grades as Australian (Mumme, 1988).

During the 1960's the price of good blue Anakie sapphires rose abruptly, largely as a result of Asian sapphire source depletion. Yellow sapphires also increased significantly in price. Because of the high demand for Anakie sapphires, particularly in Bangkok, the 1970's marked the introduction of large scale mining machinery to these gem fields to increase production.

Geology of the Anakie Gem Field

Anakie sapphires are derived from the weathering of a wide cover of basaltic ash (Mumme, 1988). Two basaltic volcanic necks, the Policeman's Knob and Mount Pleasant, remain of the Tertiary volcanoes in the Anakie field area that are thought to have carried sapphires (along with spinels, garnets, and zircons) to the surface. Corundum has been found *in situ* in the basalt of Policeman's Knob. It is also believed that volcanic necks once situated in the Drummond Range, but long since eroded away, effected the distribution of much of the gem corundum in the area (Mumme, 1988). The basalts are alkaline in character.

While sapphires have been observed *in situ* in basalts in the Anakie field, they are mined only from alluvial deposits. Some basalt pebbles hosting sapphires are found in the gravels. The sapphire-bearing gravels of the Anakie gem field are underlain by Ordovician metamorphic rocks intruded by plutonic rocks, including the Devonian Retreat granite, some diorite and granodiorites (Mumme, 1988). The granite is locally intruded by the Hoy basalt, which contains olivine phenocrysts and is thought to be the source of the sapphires. According to Mumme (1988), in the early days of mining it was reported that a pale blue sapphire possessing a thick scaly coating on one side together with an abundance of pleonaste was picked

up at an elevation of 500 feet at the top of a hill. The Hoy basalt contains pleonaste as a common inclusion, but in corroded form.

Besides sapphires, black spinel (pleonaste-variety ceylonite) and zircon are found in relative abundance in the Tomahawk Creek gravels.

B.2 Sri Lanka (formerly Ceylon)

Sri Lanka has been a producer of gem quality corundum for over 2000 years. It is now the most important source of fine quality corundum in the world in terms of quantity, variety, and size (Newman, 1991).

Sapphire mining in Sri Lanka is widespread in the southern half of the island. More than 40 different gemstones are found in Sri Lanka; the most important are ruby, sapphire, chrysoberyl (such as the prized honey colour and apple green varieties), spinel, tourmaline, zircon, beryl, topaz, moonstone (oligoclase or orthoclase), hessonite garnet, almandine and pyrope, crystalline quartz, and sinhalites (MgAlBO₄). According to Mumme (1988), rare collector items found in the gem gravels include kornerupine $(Mg_4(A1,Fe^{3+})_6(Si,B)_4O_2(OH))$, diopside, green sphenes, pale yellow danburites $(CaB_2(SiO_4)_2)$, green and blue apatite, axinite, enstatite, blue fibrolite (sillimanite), violet-blue iolite (cordierite), and the very rare taaffeite (Mg_3Al_8BeO_6).

Mining is conducted on three types of secondary deposits: (1) recent alluvial gravels in the major rivers and their tributaries, (2) alluvial placers, and (3) on eluvial placers. In the latter two cases, small pits are dug to reach the gem-bearing gravel which is then washed by hand in large baskets. The rich gem gravels produce sapphire of different colours: blue, indigo, green, white, pink, orange, yellow, as well as a few padparadsha (orange sapphire with pink overtones).

B.2.1 Geology

Precambrian rocks dominate the geology of Sri Lanka. Metamorphic Precambrian rocks are divided into the Highland Group, the Southwest Group and the Vijayan Complex. Sapphires and other gems are mined from the recent alluvial deposits which have their source in the Highland Group. Continental drifting and collision of the two Vijayan blocks produced metamorphism of aluminous sediments, converting them into amphibolite and granulite facies rocks, with gem quality corundum, garnet, sillimanite, cordierite, andalusite, spinel, garnet, beryl, chrysoberyl (alexandrite and cat's eye), topaz, tourmaline, zircon, and quartz (Mumme, 1988). The gneisses are richer in spinel and tourmaline, while the granulites contain beryl, topaz, and sapphire (Mumme, 1988).

Sri Lanka sapphires might be derived from the erosion of high grade metamorphic rocks such as cordieritebiotite-sillimanite gneisses. It is also possible that some of the gemstones, including sapphires found in the alluvial deposits on the island, came from other parts of the super-continent Gondwana Land which eventually broke up as a result of continental drift. Comparable metamorphic grades of rock occur in southwest Australia, southeastern India and Antarctica.

B.3 Thailand

Thailand is not only an important source of corundum but is also an important cutting center for corundum and other gems. It is estimated that there are some 800,000 gem cutters in Thailand today. Rough is imported from Australia, Sri Lanka, Cambodia and Burma, and is cut and sold in Thailand, with occasional misrepresentation of origin. Commercial sapphire mining in Thailand occurs at three major localities: (1) Chanthaburi and Trat Provinces; (2) Bo Ploi District, Kanchanaburi Province, western Thailand; and (3) Den Chai District, Phrae Province, northern Thailand.

B.3.1 The Chanthaburi and Trat Provinces

The Chanthaburi and Trat gem fields are located approximately 330 km east-southeast of Bangkok (Keller, 1982). Sapphires are found in a coarse yellow or brown sand overlying a bed of clay or basaltic rock. These beds are mostly within six or eight feet of the surface, although some of the sapphire workings are twenty or more feet in depth (Mumme, 1988). The gem gravel varies in thickness from 0.3 m to 1 m (Keller, 1982). Sapphires in this area are associated with small plateau-like bodies of basalts (with volcanic necks at Khao Ploi Waen and Khao Wua) which are similar to those occurring further east in the Pailin gem district of Kampuchea (Cambodia), which was formerly part of Thailand. The Chanthaburi-Trat basalts are alkaline, olivine-bearing and contain augite, pyrope garnet, calcic plagioclase, zircon, spinel, and magnetite (Keller, 1982). They locally contain spinel-rich lherzolite nodules, which, according to Keller (1982), may be the source of the corundum. Although sapphires actually found in the basalt matrix are very rare, the spatial distribution of sapphires (and rubies) around the basalt flows suggests that the corundum is derived from the basalts. Jobbins and Berrangé (1981) suggest that the corundum is xenocrystic in the lavas while Vichit (1978, from Hughes, 1990, reference not given) favors in situ crystallization. According to him, partial melting of mantle materials at depths of 65 to 95 km generates basaltic magma which, during its long ascent, is contaminated by wall rock material; this induces corundum crystallization.
The Chantaburi gem field produces mainly green, blue, yellow, and black sapphires, but pink, purple, and lavender colours are also found. Sapphires range in size from less than a millimeter to 10 cm in length, but the larger stones are not of gem quality (Keller, 1982). Some mines are major producers of rubies.

B.3.2 The Bo Ploi District, Kanchanaburi Province, Western Thailand

The Kanchanaburi gem field is located some 130 km northwest of Bangkok. It is Thailand's major producer of blue sapphires (Hughes, 1990). Large stones (20 carats or greater) are frequently found. Occasionally, yellow, pink and star sapphires are discovered. Kanchanaburi sapphires resemble the heat-treated blue sapphires from Sri Lanka. They are usually milky and have strong colour zoning (Hughes, 1990).

B.3.3 The Den Chai District, Phrae Province, Northern Thailand

Sapphires mines of the Phrae Province are located some 1000 km north of Bangkok. This area has been mined only since the 1970's. The Mae Sung field is known for excellent blue and black star sapphires. Green sapphires, poor quality rubies, and red spinel are also found. The source of the famous Burmese blue star sapphire is just north of this area. These sapphires are a very deep inky-blue colour; however, large stones (5 carats or more) are rare (Hughes, 1990). The sapphires are mined from recent alluvial deposits derived from basalts. They are found associated with black spinel (magnetite), sanidine, augite, olivine, and zircon.

B.3.4 Sapphire Characteristics

Thai and Australian sapphires have similar characteristics. The hue (for blue stones) ranges from violet blue to greenish blue. The tone ranges from very dark to medium dark. The hue is often masked by a fair amount of gray and there tend to be numerous black extinction areas (Newman, 1991).

B.4 Brazil

Rubies and sapphires have been found in the states of Bahia, Ceara, and Goias (Newman, 1991). Almost any hue of green, yellow, orange, red, blue, and purple can be found. The clarity of the stones is often low, and they are usually cut into cabochons.

B.5 Cambodia

Although Cambodia's production is small, the colour of the stones (sapphires and rubies) is very good, ranking between those of Burma and Sri Lanka.

Rubies and sapphires were discovered in Cambodia around 1874. The sapphires occur at several widely scattered localities including Pailin, which is located not far from the Chantaburi gem field in Thailand, Khum Samlot (also called Bar Khal Stung), situated about 50 km SE of Pailin, Phnum Chnon, which lies about 300 km NNE of the Pailin deposits, and Chamnop, which is located some 150 km SE of Pailin (Mumme, 1988). Khum Samlot is mostly a ruby producer.

B.5.1 Geology of the Pailin Deposit

The sapphires are mined from alluvial deposits derived from basalts. Pailin basalts have been dated to 1.7 ± 3 Ma (Mumme, 1988). Jobbins *et al.* 's (1981) study of the same basalts yielded dates between 2.14 and 1.4 Ma. They also dated the large basaltic bodies in Vietnam and eastern Cambodia and obtained ages of up to 12 Ma. Gem minerals also found include ruby, zircon, garnet, and spinel.

The southern part of the Pailin district, comprised of Triassic sandstones and greywackes, was uplifted by block faulting during the Himalayan Orogeny in Tertiary times. Uplift was accompanied by intrusion of small gem-bearing basaltic bodies in the vicinity of the fault zone with subsequent extrusion of lavas (Mumme, 1988, Jobbins *et al.*, 1981). Rapid erosion of the lava during Tertiary times produced alluvial gem-bearing deposits that were subsequently reworked into present river alluvium in Quaternary times. Jobbins *et al.* (1981) demonstrated by detailed mapping of the area that only those rivers draining the basaltic bodies and flows carried gemstones (sapphire, ruby, zircon, and garnet). Gems were also found *in situ* in weathered basalt and in the soil overlying basaltic bodies.

Four separate extrusions of lava occurred in this general district, forming small hills: the Phnum O Tang lavas, the Phnum Ko Ngoap lavas (the eroded remnants of a volcanic cone), the Phnum Yat lavas, also a volcanic cone, and an unnamed volcanic pipe only 200 m in diameter (Jobbins *et al.*, 1981). The first two are mostly ruby producers, while Phnum Yat yields only blue sapphires. A study of the lavas from Pailin by the latter authors revealed that they are basic to ultrabasic silica-deficient, very similar to average basanites, and that they are similar in composition to the lavas from the Chantaburi-Trat (Thailand) gemfields. The Pailin basalt composition in wt.% with average basanite composition in brackets is (Jobbins *et al.*, 1981): SiO₂ 43.50 (44.30), TiO₂ 2.82 (2.51), Al₂O₃ 13.91 (14.70), Fe₂O₃ 3.62 (3.94), FeO

8.5 (7.50), MnO 0.15 (0.16), MgO 8.48 (8.54), CaO 10.78 (10.19), Na₂O 3.30 (3.55), K₂O 2.20 (1.96), H₂O⁺ 0.78 (1.20), H₂O⁻ 0.43 (0.42), P₂O₅ 0.84 (0.74), rest 1.03 (0.18), total 100.34 (99.89).

Pailin basalts are porphyritic with phenocrysts of augite, euhedral olivine (often serpentinized) and feldspars, and with megacrysts of magnetite, ilmenite, spinel, clinopyroxene, garnet, and phlogopite. The groundmass is composed mostly of analcime with some feldspar (oligoclase-andesine); microlites of augitic pyroxene are sometimes identifiable. The lavas contain vesicles filled with opaline and chalcedonic silica, andesine and radiating zeolites (Jobbins *et al.*, 1981). The lavas were identified as analcime-basanite by Jobbins *et al.* (1981), who suggest that the megacrysts are in fact xenocrysts. The crystals possess surface features suggesting corrosion (or disequilibrium) with respect to a magma. The authors suggest that the xenocrysts were formed at great depths, by metamorphic and/or metasomatic processes, and were subsequently intruded rapidly with the basic magma.

B.5.2 Sapphire Characteristics

Colourless, yellow and green sapphires are absent in the Pailin area (Hughes, 1990). Blue stones range in colour from a medium to deep blue, and according to Hughes (1990), in some cases the blue sapphires may be among the world's finest, with only those from Kashmir and Burma being better. Colour zoning is common and many sapphires are cloudy due to microscopic inclusions (Jobbins *et al.*, 1981). Pailin sapphires are usually heat treated to remove these imperfections.

B.6 China

Sapphires have recently been found in three localities in China: near the city of Mengxi in the Fujian Province, near Menchang on Hainan Island, and near Taxkirgan in the Xinjiang Uygur Province. The main sapphire occurrence is the Lindi mine located near Mengxi. Sapphire, along with spinel, enstatite, zircon, peridot, and pyrope garnet is mined from gravel beds of the Ginki Greek river. A few alkali basalts have been mapped in the region, some of which are sapphire bearing. The gravel could come from the erosion of these basalts.

The deposit of Hainan Island was, in 1988, under geological investigation and according to Furui (1988), could be the largest sapphire deposit in China. The sapphires are found in alluvial gravels, probably weathered from alkali basalt (Furui, 1988). The gravels also contain abundant pyrope garnet, black spinel, pyroxene, olivine, and zircon.

Chinese sapphires range in colour from dark blue, blue, and greenish blue, to bluish green, green and yellow-green. Some light bluish green, purplish blue, and blue-gray stones are also found (Furui, 1988). Their average weight is about 2 carats (Newman, 1991).

B.7 Columbia

According to Newman (1991), commercially important deposits of sapphires have been found in Colombia in the past few years. Most of the stones are blue, but they also come in fancy colours such as yellow, pink, lavender, and brownish green.

B.8 Europe

Although gem quality corundum has not yet been found in Europe, it is interesting to note the occurrence of corundum in basalt in the Rhine valley, and at Le-Puy-en-Velay in France, as well as the corundum bearing

tholeiites on the Island of Mull, Scotland. Corundum also occurs in Bohemia, but the geological setting is not known.

B.9 India

India is well known for its famous Kashmir sapphires which were actively mined between 1881 and 1887, with sporadic mining until 1937. The Kashmir mines are now officially closed.

The deposit is located in a small mountain saddle adjacent to the Vale of Kashmir (or Cashmere) in the Paddar region of the Zanskar district of the Great Himalayan Mountains, several days journey southeast of Srinagar, the capital of Kashmir (Mumme, 1988, Hughes, 1990).

The Kashmir mines are located in a steep rock face at the head of a valley at an elevation of approximately 4500 m. The deposit was discovered as a result of a massive landslide that exposed sapphire-bearing pegmatite lenses occurring in an actinolite-tremolite rock. An alluvial deposit was also found on the valley floor, located 250 m below the primary deposit. The sapphires were of generally lower quality at this locality (Hughes, 1990). Mining operations commenced about 1881 and were conducted on both the alluvial primary deposits until the latter became exhausted in 1887 (Mumme, 1988). Mining was first conducted by gem dealers, until the Maharajah of Kashmir, who held the mining rights, sent troops to take charge of the operations. After 1887, mining was conducted sporadically either by companies leasing the property, the government itself, or by smugglers, who were aided by the harsh climatic conditions (due to the high elevation of the deposit), which restricted mining operations to a period between mid-July and the end of September. In 1907, a "New Mine" was found a few hundred meters southeast of the first deposit. However, the quality of the sapphires was very poor at this new locality. Between 1933 and 1943, about 850,000 carats of both sapphires and corundum were mined from the entire deposit; between 1945 and

1946, 1,070,000 carats (mainly of corundum) were recovered, and the last official production, between 1949 and 1951, produced 1,450,000 carats of varied grades of sapphires and corundum (Mummes, 1988).

B.9.1 Sapphire Characteristics

Kashmir sapphires occurs as spindle-shaped hexagonal bipyramids. The blue colour is found mainly at the outer edges of the crystals, especially at the tips, while the core of the crystal remains colourless. Sapphires from the "New Mine" and the alluvial deposit show corroded faces, with little of the blue colour left (Hughes, 1990). Most of the stones recovered from this locality were blue, bluish white, or bluish gray, and it was quite common to find crystals exhibiting a difference of colour in their various parts. The finest sapphires exhumed from the area possess a rich velvety cornflower blue colour, and today they remain the standard with which all others are compared (Hughes, 1990). These sapphires have a tone between medium and medium dark. Areas with dark extinction are at a minimum and their colour looks good in any type of light; daylight, incandescent, or fluorescent (Newman, 1991).

B.9.2 Geology

The sapphires occur in pegmatite lenses scattered through an actinolite-tremolite rock. The lenses are about 6 m in length by 0.3 m in width and are 3 m deep (Mumme, 1988). At the surface, the lenses are composed of tough clay which gives way at depth to solid feldspar rock in which crystals of corundum are firmly embedded along with some garnet and tourmaline (Mumme, 1988). Kyanite and euclase are also sometimes present (Mumme, 1988). These kaolinized lenses are encased in large envelopes of hard material composed largely of actinolite and tremolite with some olivine and talc (Mumme, 1988). The pegmatite lenses and actinolite-tremolite rock are located almost at the summit of a mountain composed of garnetiferous gneiss, graphite-biotite gneiss, and hornblende gneiss (Hughes, 1990), which form the

dominant rock types of the district (Mumme, 1988). The thickness of the sapphire-bearing rock is not known.

Badyal proposed (in Mumme, 1988) that gem bearing pegmatites, as well as sapphire-corundum bearing gneisses, are associated with the actinolite-tremolite gneiss, which is regionally extensive. At Dangel, 3 miles SSE of Soomjam, a small hamlet located in the valley where Kashmir sapphires occur, corundum-sapphire crystals about 3.5 cm long are sparingly distributed in a thick pegmatite vein, which is bordered by a very narrow layer of hornblende gneiss with corundum crystals of a deeper colour up to 5 cm long by 2.5 cm wide making up some 20% of the volume of the rock. Corundum is also present in the neighbouring garnet biotite gneiss. Forming a fringe on the eastern side of a large actinolite-tremolite mass 250 feet long by 80 feet wide, the whole assemblage is in fact a southern continuation of the main rock types of Soomjam (Mumme, 1988).

B.9.3 Other Occurrences in India

Sapphires are also produced in small amounts in southern India. One interesting area is situated near the village of Kangyan in Madras State. The sapphires found at this deposit yield very good fancy colour stones (Mumme, 1988).

The state of Mysore produces star sapphires (and rubies). The material is very opaque but the star is good. Furthermore, they are no more expensive than synthetic star corundum.

B.10 Kenya

Kenya is best known for its fine-coloured ruby that often equals Burmese stones. Dark-blue sapphires also occur at Garba, located about 128 km northeast of Mt. Kenya. These stones strongly resemble those from Australia. According to Hughes (1990), it does not appear that the deposits are being exploited, due to low quantities of facetable material.

B.11 Malawi (formerly Nyasaland)

Sapphires have been mined in this part of Africa since 1965. Colours include good blues, yellows, grayish greens to pale green, and pink. Mining is conducted under government control. Little is known about the geology of this occurrence.

B.12 Malagasy Republic (formerly Madagascar)

Although no commercial deposits of sapphire are found on the island, reddish, bluish, and greenish corundum occurs associated with spinel, white diopside, and tremolite in some limestones (marbles). Ruby also occurs at Gogogoga, in a green mica schist. Corundum is found in alluvial deposits, together with spinel, yellow gemmy chrysoberyl, topaz, beryl, almandine, garnet, tourmaline, and quartz.

B.13 Myanmar (formerly Burma)

Although Burma is best known for its high quality rubies, it is also renowned for its blue sapphires, second only to Kashmir in terms of prestige. The Mogok Kyat-Pyin area in Burma was an important producer of high quality gem corundum, particularly ruby, for 800 years, until 1962. At that time, the government of Burma nationalized the mines and production virtually ceased. Until recently, the few Burmese stones seen on the market came mainly from illegal mining and smuggling through Thailand and India. The last few years have seen an increase in production, with the Myanmar Gems Enterprise (MGE) actively mining the rich gem fields of Burma with modern techniques. The MGE was founded in 1989 and is operated by the government. The following areas are current producers of sapphires (from Kammerling *et al.*, 1994): the Mogok Stone tract, the Momeik (formerly Mong Mit) and Mong Hkak areas in Shan State, and the Twingire area in Sagaing State. Mines from the Mogok Stone tract area will be described in the next section; information for the other areas is unavailable.

The Yadanar Kaday-Kadar mine, 22 km southwest of Mogok, produces mainly blue sapphire, with lesser amounts of ruby, pink sapphire, and other gems. It operates both on eluvial and alluvial deposits and is the most productive of the MGE-operated sapphire mines. The Shwe Pyi Aye mine, within the township of Mogok, is a secondary deposit producing mainly fine-quality rubies. Pink sapphires, red spinels, and minor amounts of blue sapphires are also recovered. The Pan Sho mine, 1.5 km northeast of Mogok, is an openpit mine operating on a secondary deposit. It produces rubies, pink and blue sapphires, and significant amounts of other gems. The Thurein Taung mine (meaning "Sun Mountain"), 23 km west of Mogok, produces sapphires almost exclusively. The host rock is an alkali-rich basic igneous rock intruded into marble, and a biotite-bearing gneiss (Kammerling et al., 1994). The Lin Yaung Chi mine, located north of Mogok, is known mainly for its occasional production of exceptionally fine rubies. In situ mining is conducted on a vein in a fault zone at the contact between a massive marble and a diopsidic marble. Along with rubies, spinel, garnet, apatite, green tourmaline, and mica are recovered. A secondary deposit is also being mined not far from the ruby mine; this produces large sapphires, spinel, garnet, apatite, green tourmaline, and topaz. The Mong Hsu (or Mine Shu) mine, 250 km north of Mandalay, produces a unique type of corundum; the stones have a sapphire core mantled by ruby. Although the crystals are unique mineral specimens, they are usually heat treated to remove the sapphire core, which often results in

fracturing due to the presence of inclusions. Both a primary deposit (in marble) and a secondary deposit are being mined. Secondary gem materials that are recovered include quartz, green tourmaline, red-brown garnet, staurolite, pyrite, and tremolite.

According to Hughes (1990), fine sapphires are found at Pingu Taung, near the town of Kathe, where very large stones have been unearthed (including one of 959 carats). According to Kammerling (1994), this mine is mainly a ruby producer.

B.13.1 Sapphire Characteristics

At Mogok, sapphires occur in blue, violet, purple, colourless and yellow colours. For blue stones the hues range from violet blue to blue. The tone is usually in the medium-dark range. Burma sapphires tend to be darker than those from Kashmir and Sri Lanka and the colour tends to be more evenly distributed. Yellow, pink, green, violet and colour-change sapphires are also found in Burma (Newman, 1991). Sapphires form about 10 to 20% of the total mining output at Mogok and they reach larger sizes than the rubies (Kammerling *et al.*, 1994).

B.13.2 Geology of the Gem Deposits

Information on the geology of the gem deposits is often very scarce and is usually incomplete. This reflects the fact that the papers are often written by gemologists for whom geology is not of prime importance. According to Hughes (1990), the rubies of Mogok are mined from marble, while the sapphires are derived from pegmatites. Mumme (1988) explains that corundum in the Mogok area is found associated with Cenozoic nepheline syenite intrusions, in contact metamorphic zones, and in metamorphosed limestone (marble). He also mentions that the main source of gem quality corundum in the Mogok district is the

"byon", or alluvial gravel, and that the source rocks for these gravels are Al-rich gneisses and marbles belonging to an important structural unit of Mesozoic or earlier age. According. to Mumme (1988), sapphires are also found in coarse crystalline marble, together with spinel, rubies, diopside, forsterite, scapolite, sphene, and garnet. Kammerling (1994) mentions two processes for the formation of primary ruby deposits: (1) contact metamorphism, and (2) regional metamorphism. Ruby occurs in a coarsegrained marble containing spinel, diopside, and phlogopite. The marble is interbedded with gneisses and is intruded by numerous syenitic, granitic, and pegmatitic bodies. Contact metamorphism, or more specifically metasomatism of limestone by pegmatite-derived magmatic fluids, results in desilification of the limestone and the formation of silica-poor minerals such as diopside, forsterite, and spinel and corundum when the CaO and SiO₂ are depleted. Regional metamorphism would have the same effect on limestone, but on a larger scale. According to Kammerling (1994), corundum would be produced by metamorphism of boehmite and diaspore [AIO(OH)]. The source of Cr for the formation of ruby is not explained in this theory. The interbedded gneisses produced by metamorphism of shale could be the source of the sapphires as shales are usually rich in iron.

B.14 Nigeria

Blue sapphires similar to those of Australia and Thailand have been produced in Nigeria during the past few years (Newman, 1991). Green, yellow, and bicoloured sapphires are also found.

B.15 Tanzania

The Tanzanian production of corundum, mainly sapphires, has recently increased significantly. Stones come mainly from the Umba River Valley, and very few other areas in the world produce as many colour

varieties of corundum.

The sapphire occurrence is located in northeastern Tanzania, 16 km from the Kenyan border, 112 km NNW of the coastal town of Tanga, and between the village of Makijimbe and the Gilevi Hills. The deposit was discovered in 1962 by local people, who, after identification of their find, decided to open a mine.

The output of the mine could be quite substantial if operated on a large scale. However, the political situation is not attractive to foreign investment. The socialist government closed down the mine in the 1970's. In 1987, the government allowed mining again, and a Japanese company negotiated a deal with the state to start heavy mining (Federman, 1990). The area is presently being mined and sapphires are offered on the market, both as cut stones and as rough.

Tanzania is also the producer of the famous "ruby in zoisite" that has seen great popularity in recent years. Rubies (more correctly called corundum in this case), reach large sizes (up to 50 cm in diameter). The contrast in colour between the purple-red corundum and the chrome-green zoisite makes this material a popular choice amongst carvers.

B.15.1 Geology

The sapphires (and rubies) occur in and around a grayish-green serpentinite pipe measuring about 2.5 km long by 1 km wide (Hughes, 1990). It is cut by pegmatite veins striking generally NNE and dipping eastwards (Hughes, 1990). The serpentinite is intruded into amphibolite-garnet gneiss, quartz-feldspar gneisses, graphite gneiss, and marble carrying phlogopite, graphite, and siliceous granulites. Associated with the pegmatites are vermiculite, chlorite, actinolite, and sometimes corundum (Hughes, 1990).

According to this author, the corundum occurs mainly in the limestones, but sapphires and rubies are found almost exclusively in the vermiculite and chlorite rock associated with the pegmatites.

B.15.2 Sapphire Characteristics

A survey by the first mine owner in the 1960's revealed that various colours were recovered from different parts of the property. One area produced pink and blue corundum, which unfortunately was almost invariably shattered, another area produced only blue sapphires, a third location yielded red corundum, and a fourth one produced padparadscha (with pink highlights) stones.

According to Hughes (1990), six of the major colour-producing ions (chromium, iron, manganese, nickel, titanium, vanadium) are present at Umba and its environs. This would appear to be the main factor accounting for the large variation in colour of the sapphires from the Umba deposit.

The gem quality material consists mainly of broken pieces up to 1.5 inches in diameter, but tabular hexagonal prisms are also found. Some stones show colour zoning, where the core is one colour and the outside of the stone is another. The best colours include blue, purple, brownish-orange (sometimes referred to, incorrectly, as padparadscha), and some rare alexandrite types, which change from greenish-gray in daylight to a purplish colour under incandescent light (Hughes, 1990). Some of the sapphires are strongly dichroic, for example changing from pale pink to dark magenta or from yellow to brown when the stone is turned. The inclusions found in these sapphires include long needle-like tubes, mineral inclusions, aggregates similar to those found in Burmese rubies, short tube-like inclusions, and oval or rounded crystals (Mumme, 1988). Ruby, deep red almandine garnet, and black andradite garnet are also found in the host rock.

B.16 United States

Corundum occurs in the United States in North Carolina, Georgia, in scattered deposits in western Montana, and in Massachusetts and New York. The latter two states are former producers of emery (a mixture of corundum and magnetite). A few sapphires and rubies have been found in North Carolina, but the bulk of the production is of industrial grades. The only state to have produced sapphire abundantly is Montana.

B.16.1 Montana

In the western Northern Hemisphere, Montana is by far the most important source of corundum. Total corundum reserves in this state might be the largest in the world. Although sapphires were recognized in the gravels of the Missouri River in 1865 (Hughes, 1990), Montana became known for its sapphires only at the end of the last century when the Yogo Gulch sapphire deposit was found and began to be mined. For 30 years, the cornflower blue, usually flawless Yogo sapphires made their way to the European market and to the well-known New York-based Tiffany jewelry stores. Richard Hughes states (in Newman, 1991) that if it were not for their small size (usually under 1 carat in the rough), Yogo sapphires might be the world's most renowned blue sapphires. Stones in the 2 to 3 carat range are rare, but equal or even surpass in terms of clarity and brightness the best quality Ceylon and cornflower blue Kashmir sapphires.

Sapphires occur in placer deposits along the Missouri River, at Rock Creek, Dry Cottonwood, Quartz Gulch, Pole Creek, Brown's Gulch, and at the Chouteau County mine. They were first recovered as a byproduct of gold mining.

The Missouri River Area

Along the Missouri River, the main areas worked for sapphire are the Eldorado Bar, 19 km northeast of Helena, and the River Castle mine. Sapphires are also recovered on a smaller scale at other bars along the river. From Helena, these include (from SSE to NNE, moving downstream) Emerald Bar and Magpie Gulch near Canyon Ferry, about 24 km east of Helena, French Bar, Metropolitan Bar, Eldorado Bar, Dana Bar, and American Bar.

Sapphire was first discovered in Montana along the Missouri River in 1865 in placer gold mining operations (Voynick, 1985). The small heavy pebbles would accumulate in the riffles of sluice boxes along with the gold. At the end of the day miners would recover the gold in the jigs, tossing away the small pebbles that had accumulated on top of the gold. In 1873, Dr. Lawrence Smith, an authority on sources of industrial corundum, wrote in the *American Journal of Science*:

"My opinion is that this locality (Missouri River) is a far more reliable source for the gem variety of corundum than any other in the United States I have yet examined."

Large scale mining did not begin until about 1891 when the Sapphire and Ruby Company of Montana Limited, a British syndicate, acquired some 3000 to 4000 acres of gem bearing gravels along the Missouri River (Mumme, 1988). Mining of the sapphires as gems was not successful, mainly due to the abundance of pastel colours; at that time, only blue sapphires and rubies were of significant value. The deposits were sporadically mined for industrial grade corundum; the pale gem quality stones often included in this grade were used for watch jewels and bearings. When cheap, easily produced synthetic corundum made by the Verneuil process entered the market in the mid 1900's, the Missouri River sapphires soon lost their market and mining on a commercial basis totally ceased. It would be almost a century before large scale commercial operations resumed. As pointed out by Pough (1993), the Verneuil process of synthesizing corundum killed the market for natural corundum at the beginning of this century, but by doing so, deposits were preserved and can now be exploited more efficiently, with the gem quality stones being used as gemstones, not as industrial minerals. This is made possible by the advent of heat treatment, which transforms the pastel colours of these sapphires to deeper, more attractive tones. Because of the heat treatment process, the Upper Missouri River placer deposits have been contributing more and more material to the world sapphire market in the last few years.

Sapphire is recovered from placer deposits occurring in gravel beds lying on benches or terraces at an elevation of up to 200 feet above the Missouri River. The most productive gravels are the ones adjacent to the bedrock. Garnet, topaz, gold, silver and platinum are found with the sapphires (Mumme, 1988).

The geology of this area includes rocks of different types and ages, such as Precambrian argillites of the Belt series, Paleozoic sedimentary rocks, Tertiary lake beds and volcanics, and Cretaceous and Tertiary igneous intrusives. At most of the bars the gravels rest on argillaceous rocks of the Belt series (Clabaugh, 1952).

According to Kunz (1893a, 1893b), a dike hosting sapphires and pyrope garnet was found cutting the slaty rock at Ruby Bar. He describes the dike rock as a vesicular andesite containing an abundance of brown mica and porphyric crystals of augite. The groundmass consists mainly of feldspar microlites with a considerable amount of glassy interstitial matter and much magnetite (this description fits the definition of a lamprophyre, possibly a monchiquite). Kunz (1893a, 1893b) proposed that the source of the sapphires was a rock of similar composition to the dike found at Canyon Ferry, and that the gravels originated north of the Missouri River as he believed they were deposited by the southward movement of glaciers. However, the gravels are river gravels and the sapphires could well have their

source in the area of the Canyon Ferry sapphire-bearing dike. The area called "Ruby Bar" by Kunz (1893a, 1893b), does not appear on any map at present; it could well be the "French Bar", the area from which Pratt (1906) described a narrow dike hosting green sapphires. This dike is located 3 miles south of Canyon Ferry.

Clabaugh (1952) describes the Canyon Ferry sapphire-bearing dike as a vesicular mica-augite andesite. It is porphyric (with biotite, augite, and perhaps phlogopite), vesicular (with chalcedony or calcite fillings), brown to gray in colour, with a glassy groundmass which has scattered minute magnetite grains and feldspar (labradorite) microlites. His description seems to indicate that the rock is in fact a lamprophyre. Garnets and blue-green sapphires occur as accessory minerals in the dike. Garnets occur as inclusions in the sapphires.

Pratt (1906) proposed that the source of the sapphires is a lava. His interpretation is based on the fact that the dike found at French Bar is small and no other sapphire-bearing dikes have been found in the area that could account for the amount of sapphires present in the Missouri River. On the other hand, no volcanic material has been found in the area, and one would think that if the source was lava, there would be some remnants.

Sapphire crystals from the Missouri River are slightly rounded and worn, but crystal faces can be recognized (Hughes, 1990). The crystals rarely exceed 0.25 to 0.5 inches in length and usually have pale tints (Kunz, 1890, Clabaugh, 1952). Colours include light-green, greenish-blue, light-blue, bluish-red, light-red, and the intermediate shades. Pale blue-green, light blue, and light green are the commonest; pale purplish-blue sapphires are not uncommon. Darker blue, pink, reddish-purple, and yellow colours are rare. The sapphires are usually dichroic. Their pastel colours rendered them unpopular at a time when deep colours were fashionable. Crystals commonly show zonation, with

cores being lighter in colour, and they sometimes show bands of colour. Sapphires from this locality are typically silky; this is due to clusters of minute negative crystals or cavities in zonally distributed linear swarms parallel to the adjacent prism faces.

Rock Creek Deposit

Sapphires were first discovered at Rock Creek about 1892 by gold placer miners (Clabaugh, 1952). The Rock Creek sapphire deposit, also called the Gem Mountain sapphire mine, is located about 26 km southwest of Philipsburg. Sapphires are found primarily in Anaconda Gulch and Sapphire Gulch. Rock Creek is one of the two areas in the states presently open to rockhounds for fee digging.

At the beginning of the century, between about 1894 and 1914, sapphires from Rock Creek were mined commercially, mainly for industrial corundum and for watch jewels and bearings, but also for gem quality stones, which accounted for about 10% of the production. Sporadic mining also occurred between 1914 and 1943 at which time mining was discontinued.

The introduction of synthetic corundum to the world market in those years contributed greatly to the commercial failure of the placer deposit mines of the Rock Creek site as well as the ones along the Missouri River. These deposits were mined mainly for industrial grade corundum, since the pastel colours of the sapphires were not competitive in a market which favored the dark blues.

During World War II, two corundum deposits were revived to meet the increased demand for industrial corundum. By 1944, when activity ended, the Rock Creek deposit and the Missouri River bars had produced over seven million carats (2 tons) of sapphire. Although a good proportion of the stones were of gem quality, the entire production was used for jewel bearings or abrasive and cutting material.

Sapphires at this deposit occur in gravels 30 to 100 feet thick. At Sapphire Gulch, the bedrock is purple argillite of the Belt Supergroup which is overlaid by Tertiary volcanics, some intrusive bodies and some conglomerates. The gravels are mainly composed of quartz-rich porphyritic igneous rocks and light gray to brown pyroclastics. Some specimens of felsic tuff are also found. At Anaconda Gulch, sapphires are found in the proximity of tuff (Clabaugh, 1952). The same author reports that sapphires have been found in small fragments of igneous rocks in the gravels, and some of the pyroclastic rocks strongly resemble the sapphire-bearing dike rock from Ruby Bar on the Missouri River. Clabaugh (1952) proposed that the sapphires may have been derived from the tuffs of the area.

Many of Rock Creek's sapphires are well-rounded (Clabaugh, 1952), suggesting long transport. Sapphires at Gem Mountain are found in a great variety of colours, but cornflower blue, velvety blue, and ruby are lacking. Pastel hues predominate (Mumme, 1988). The sapphires are similar to those found along the Missouri River except that a wider range of colours is common, and many of the stones are more strongly coloured (Clabaugh, 1952). The most frequent shades are pale blue, blue green, green, pink, and yellow. Colour zoning is common (Zeihen, 1986). Blue or blue-green sapphires with a central orange or yellow spot are often seen, and some padparadscha sapphires are occasionally found (Zeihen, 1986).

The Rock Creek sapphires are similar in size and form to those found along the Missouri River near Helena. Some of the crystals are sharp and distinct, with pitted surfaces, while others are abraded and rounded. Most of the crystals are hexagonal plates, many are thick enough to be approximately equidimensional, and a few are prismatic crystals with length greater than width. Crystal forms are commonly the same as those developed by the Missouri River sapphires; basal pinacoids, prisms, dipyramids, and unit rhombohedra (Clabaugh, 1952).

Canyon Ferry

At this locality, transparent to translucent pale sapphires are recovered from gold operations, and a few crystals have been found *in situ* in small dikes (Clabaugh, 1952).

Dry Cottonwood Creek

These deposits are located about 12 miles northwest of Butte. Sapphires were found in 1889 in test panning at the highest spring on the south fork of Dry Cottonwood Creek, at an elevation of 6,950 feet (Clabaugh, 1952). Mining on a large scale began in 1907 and ended in 1911. During this period, industrial corundum and sapphires were produced, but according to Clabaugh (1952), no mining records are available. The area is now open to the public for digging.

The bedrock is largely granite of the Boulder batholith and quartz latitic rocks of the Lowland Creek volcanics (Zeihen, 1986). The creek cuts through porphyries in the upper 2 miles of its course and through granite and quartz monzonite further downstream. The source of the sapphires was reported (by Kunz, 1904) to be an igneous rock containing both sapphires and garnets.

Sapphires of the Dry Cottonwood Creek area are usually small and of poor colour (Sterrett, from Clabaugh, 1952). The predominant colours are deep and light aquamarine and pale yellowish green. Other colours sometimes encountered include smoky blue, light and dark topaz yellow, straw yellow, yellowish green, light and dark pink, lilac, amethystine, colourless, and nearly ruby red stones. Many stones are dichroic. Some stones are spotted, notably the aquamarine coloured sapphires with a red spot in the center. The proportion of waterworn sapphires is not large, the stones being mainly rough crystals or crystal fragments with etched and corroded faces (Sterrettt, from Clabaugh, 1952). A few small red and cinnamon-red garnets are found in the concentrate with the sapphires.

Mines Open to the Public

The Chaussee and Cornish Sapphire Mines in the Rock Creek area were open to the public on a fee basis in 1979. On the Missouri River the Eldorado Bar, the Guffey Mine (west of Canyon ferry) and the Castle Mines were also opened to rockhounds for digging in 1979. The Eldorado Sapphire Mine, Gem Mountain Sapphire Mine, and the French Bar Mine were popular digging areas in 1990.

Others

Other known occurrences of corundum in Montana, of lesser economical importance, include Benton Creek, Lowland Creek, Browns Gulch, Big Spring Gulch, Camp Creek, Seetwater Creek, the Alder dredge piles, and the Gallatin deposits (Zeihen, 1986).

Corundum of metamorphic origin occurs in Gallatin and Madison Counties, southwest of Bozeman, Montana. It is dull in appearance, translucent, blue gray to lilac, and occurs in large, elongated crystals. It is suitable for use as abrasive only (Clabaugh, 1952). This corundum is found in Precambrian gneisses. These include hornblende-garnet gneiss interlayered with quartzite, feldsparrich gneiss, sillimanite gneiss and sillimanite-corundum gneiss, and feldspar-mica granulite. Minerals usually found in the gneiss are feldspars, hornblende, quartz, micas; more restricted in occurrence are rutile, chlorite, vermiculite, corundum, sillimanite, magnetite, tourmaline, and other minerals (Clabaugh, 1952). The sillimanite-corundum gneiss occurs in lenses and is composed mainly of feldspar (microcline, perthite, plagioclase), mica (biotite, muscovite), and sillimanite, with accessory corundum, rutile, sphene, zircon apatite, tourmaline and magnetite. The corundum-bearing layers are enclosed in a thin envelope of friable, dark-coloured gneiss, which is composed mainly of vermiculite and feldspar and includes some garnet, quartz and corundum. The corundum is gray-blue in colour and varies in size from 0.1 inch to 1 foot. Crystals of several inches in length are common.

B.17 Zimbabwe (Rhodesia)

Zimbabwe (Rhodesia) has been a producer of high-quality blue and black star sapphires since 1968. The Barauta mine, located in northeast Zimbabwe, produces a good range of blue stones, often approaching the finest Burmese blue. Zimbabwe sapphires occurs as squat barrel-shaped hexagonal crystals from 0.8 to 3.1 mm in length, which often exhibit a yellow brown opaque crust which makes it difficult to determine the quality and colour of the crystal. The mine operates on an alluvial deposit. A primary deposit associated with a pegmatite is also known from this area but has not been worked (Mumme, 1988).

B.18 Others

Sapphires have been found in Burundi, but, according to Newman (1991), little is known about the occurrence. A small amount of pink and violet sapphire is produced in Nepal, but it is usually heavily included. Ruby and some purple to violet sapphires are found in Pakistan, but the material is mostly of cabochon grade (Newman, 1991). Sapphire of grayish-blue colour is found in Zaire, according to Newman (1991).

APPENDIX C

SUMMARY OF LAMPROPHYRE CLASSIFICATION SCHEMES

C. SUMMARY OF LAMPROPHYRE CLASSIFICATION SCHEMES

C.1 Introduction

Lamprophyres form a heterogeneous group of rocks with a wide range of compositions. The name is derived from the Greek *lampros porphyros* meaning "glistening porphyry". Lamprophyres can be defined as alkali-rich porphyritic hypabyssal rocks showing intermediate to very low SiO₂ contents with a moderate to high colour index, carrying essential primary amphibole and/or mica, and typified by lack of felsic phenocrysts and groundmass olivine (Rock, 1977). They weather easily and show characteristic alteration. Lamprophyres often have a panidiomorphic texture. They are widely distributed and form extensive regional or radial swarms (Rock, 1977). Lamprophyres always form at a late stage in any igneous event, occurring as dikes, more rarely as plugs and sills, and infrequently as vents and lava flows, accompanying aplites, pegmatites and carbonatites. Their late emplacement is likely responsible for their texture and hydrous mineralogy. Volatiles are usually concentrated at the end of magmatism and will favour growth of large pyroxene or amphibole phenocrysts while inhibiting feldspar growth. Lamprophyres often carry xenoliths of sediments, granite or basic rocks and/or megacrysts of amphibole, pyroxene or alkali feldspar. Diatreme facies are not uncommon.

Lamprophyres are one of the last group of rocks to receive a coherent terminology. Streckeisen (1979) subdivided the lamprophyre group into three classes: calc-alkaline, which includes the minette, vogesite, kersantite and spessartite varieties; alkaline, which is subdivided into camptonite, monchiquite and sannaite; and "melilitic" lamprophyres, which include alnoite (with melilite) and polzenite (with feldspathoids plus melilite). Streckeisen's (1979) ultramafic lamprophyre (or melilite) classification scheme fails to accommodate melilite-free but carbonate-rich lamprophyres and ultramafic lamprophyres (UML) with minor amounts of alkali feldspar. Streckeisen's classification is based on the QAFP (quartz-

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feldspar-foid) double triangle and colour index. The ultramafic lamprophyres often have a colour index of around 90, and a small modal variation of felsic minerals can drastically change the QAFP field. Furthermore, ultramafic lamprophyres can contain melilite and/or carbonates, which are light-coloured but are considered mafic.

A major step forward on the understanding and characterization of lamprophyres was made possible by the reviews published by Rock (1977, 1984, 1986, 1991). Rock compiled all the literature published on lamprophyres, including analyses, mineralogical characteristics, relations between each other and with other igneous rocks, mineralogical and chemical characteristics of the sub-classes, etc., and summarized the information in three review papers (1977, 1984, 1986) and a book (1991) on lamprophyres (in general), calc-alkaline lamprophyres, ultramafic lamprophyres and lamprophyres. For a comprehensive study on lamprophyres the reader is referred to these publications; only a summary of their characteristics and subdivisions will be given here.

Following Rock's reviews on lamprophyres, Streikeisen's (1979) classification scheme was modified by Le Maitre (1989; in Rock, 1991) and this was approved by the IUGS Subcommission on Igneous Rock Systematics. In this scheme there are five classes: (1) calc-alkaline (shoshonitic) lamprophyres (CAL); (2) alkaline lamprophyres (AL); (3) ultramafic lamprophyres (UML); (4) lamproites (LIL); and (5) kimberlites (KIL). The ultramafic lamprophyre class is the equivalent of Streikeisen's (1979) "melilitic" lamprophyres which were renamed by Rock (1986). In the new scheme any attempt to fit lamprophyres into the QAFP double-triangle is abandoned. In his book on lamprophyres, Rock (1991) made some modifications to the scheme, such as retaining names such as ouachitite, damkjernite and aillikite, not approved by the IUGS. He also renamed lamproites according to locality-type due to dissatisfaction with the IUGS classification, and he considered kimberlites to represent a class and not a single rock type. In this scheme, kimberlites and lamprophyre group; this is contested by Mitchell (1986, 1989, 1991b).

Table C.1: Classification of lamprophyric rocks including varietal names (from Rock, 1991).

alc-Alkaline (Sh Lamprophyres	oshonitic) (CAL)	Alkaline Lamprophyres (AL)	Ultramafic Lamprophyres (UML)	Kimberlit	cs (KIL)		Lamproites (LIL)	
abyssal	Plutonic			Non- Micaceous (K1)	Micaceous (K2)	Olivine- Lamproites	Fitzroyites (LF) Jumilites (LJ) Wyomingites (LW)	Lamproites transitional to CAL
inette santite ssartite gesite	Appinite Suite /augnerite Series	Camptonite Monchiquite Sannaite	Aillikite Alnoite Damkjernite Ouachitite Polzenite	Transitional Aillikite	Kimberlite- s (KU)	Olivine- Lamproites (LO)	Lamproite	Cocite (LC)

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Because kimberlites, lamproites and lamprophyres are distinguished not only by their mineralogy but also by their geochemistry, it is sometimes impossible to tell them apart by visual analysis alone. Kimberlites (and lamproites) have often been described as lamprophyres, or lamprophyric rocks only on the basis of field work; Rock argues that because these three types of rocks can be confused in the field, they should belong to the same rock classification. Further lab analyses would provide information for proper classification of the rock. The different rock types included in the five classes are given in Table C.1. Rocks belonging to the first three groups of lamprophyres (calc-alkaline, alkaline, and ultramafic) may also be distinguished by the mode of light-coloured minerals present; this is shown in Table C.2.

C.2 Calc-Alkaline Lamprophyres

Calc-alkaline or shoshonitic lamprophyres are mildly potassic (Na \leq K), intermediate in composition and nearly saturated. They are most frequently associated with post-orogenic granites or shoshonites (Rock, 1977). Classification of calc-alkaline lamprophyres is based on the presence of alkali-feldspars/plagioclase and biotite/amphibole (Table C.3).

CAL and AL lamprophyres can be distinguished by the presence or absence of quartz; CAL have quartz/plagioclase parageneses while AL rocks show nepheline/plagioclase parageneses. None of the other lamprophyre classes (UML, KIL, LIL) contain plagioclase (Rock, 1991).

Rock (1977, 1984, 1986, 1991) developed screens to help geoscientists discriminate between the different groups of lamprophyres. The modal and mineralogical screens are presented in Table C.4. Chemical screens for CAL, AL, and UML lamprophyres have been tabulated together in Table C.5. Similarly, CIPW normative screens are given in Table C.6 for the three types of lamprophyres.

Light-Coloured Minerals	Plagioclase > Alkali Feldspar →→	Alkali Feldspar > Plagioclase →→	No Feldspars →→	Melilite, No Feldspars →→
↓ No Na-foids ^c or leucite; minor quartz	Kersantite Spessartite	Minette Vogesite	Verites ^{d,h}	
↓ Leucite; no Na-foids [°]		Jumillites ^{d,f}	Orendites ^{d,g}	
↓ Na-foids [°] , no leucite	Camptonite	Sannaite	Monchiquite ^d	Polzenite
↓ Carbonate ^e , Na-foids ^c		Damkjernite ^j	Ouachitite	Alnöite
↓ Carbonate ^e essential, no foids			Aillikite Kimberlite ⁱ	

Table C.2: Classification of lamprophyric rocks by light-coloured minerals^{a,b} (from Rock, 1991).

^a In terms of dark-coloured minerals, *all* lamprophyres carry essential phlogopite, biotite, amphibole (calcic, sodic-calcic or alkalic), or both, generally together with olivine and clinopyroxene.

^b \rightarrow arrows indicate direction of increasing undersaturation with SiO₂.

°Na-foids are analcime, cancrinite, haüyne, nepheline, nosean and/or sodalite.

^dRocks commonly containing glass, which may occlude foids/feldspars, but is not considered in classification.

^ePrimary magmatic carbonate (calcite, dolomite, or other Ca-Mg-Fe-Ba carbonates), where distingushable.

^f Includes cancarixite, cocite, jumillite.

⁸Includes cedricite, fitzroyite, kayanite, mamilite, orendite, wolgidite, wyomingite.

^hIncludes fortunite, madupite, verite.

ⁱ These two rock types have the same olivine-phlogopite-calcite-ilmenite ± diopside mineral assemblage; they can only be distinguished on textural features (kimberlites have more rounded olivine macrocysts, higher Si/Al and Mg/Ca whole rock ratios, generally more Mg-rich ilmenites, no amphiboles, etc.).

^j Accessory alkali feldspar only, no plagioclase.

Cpx + Altered Olivine +	Quartz (Accessory) +		
	Alkali Feldspar	Plagioclase	
Biotite	Minette	Kersantite	
Green-Brown Hornblende	Vogesite	Spessartite	

Table C.3: Classification of calc-alkaline lamprophyres (from Rock, 1977).

Table C.4: Modal, minealogical, chemical and normative screens for calc-alkaline lamprophyres (from Rock, 1984).

Modal Screen (Minerals in Volume%)

- (1) [Amphibole + biotite] > 20; where [olivine + clinopyroxene] > [amphibole + biotite] > 20, the name "pyroxene lamprophyre" (pyroxene > olivine) or "olivine lamprophyre" (olivine > pyroxene) may be used, but generally, olivine < 10.
- (2) Quartz and analcime both < 10.
- (3) 35 < Colour index < 67.
- orthopyroxenes, perovskite, pigeonite, primary muscovite, pseudoleucite, (Na, K) silicates with (Zr, Nb, Ti, Ba; cossyrite, eudialyte, noonkambahite, (4) Absent minerals: armalcolite, fayalitic olivines, feldspathoids (other than analcime), K-rich amphiboles (potassium richterite), kaersutite, melilite, priderite, wadeite), titanaugite, wollastonite.

Mineralogical Screen (Oxides in Weight%, Ratios and End-Members in Molecular%)

Olivine: 75 < Fo < 92.

Pyroxenes: Mg/(Mg + Fe) > 60; Ca/(Ca + Mg + Fe) > 40; $TiO_2 < 2$; $AI_2O_3 < 6$.

Amphiboles: MgO > 10, $Na_2O > 1$; $0.3 < K_2O < 2$; $1 < TiO_2 < 3.5$.

Biotite: Mg/(Mg + Fe) > 50; $12 < Al_2O_3 < 20$; $TiO_2 < 8$.

K-Feldspar: Or > 50; $Fe_2O_3 < 2$.

	Calc-Alkaline Lamprophyres		Alkaline Lamprophyres	Ultramafic Lamprophyres	
	(from Roo	ck, 1984)	(from Rock, 1977)	(from Ro	ck, 1986)
	Outer Limits	Typical	Typical	Outer Limits	Typical
SiO ₂	42-62	46-57	38-47	15-40	25-35
Al ₂ O ₃	9-20	11-18	8-20	2-18	4-10
Fe ₂ O ₃	< 7	1-5			
FeO	< 9	3-7			
FeO _T	4-11	5-10	< 15	5-30	10-15
MgO	1.5-13	3.5-9.5		3-26	10-20
CaO	1.5-12	4-9		5-30	10-20
Na ₂ O	0.5-5	1.5-4	< 6	< 7	< 3
K ₂ O	0.5-10	1-6	< 6	< 5	< 3
H ₂ O	< 4	0.5-4		< 20	< 8
TiO ₂	0.3-3	0.5-2	< 6.0	< 6	< 4
P ₂ O ₅	< 2	< 1.1	< 3	< 6	< 2
MnO	< 0.4	< 0.2		< 0.5	< 0.3
CO ₂	< 7.5	1-5		< 20	< 15
(Na + K)/Al				0.1-2.5	0.5-1.1
K/(Na + K)	M: 40-90	20-70		5-100	30-70
	V, K, S: 10-80				
$\frac{Mg/(Mg + Fe^{2+})}{Fe^{2+}}$	40-80	50-75		40-90 ^a	60-80 ^a

Table C.5: Chemical screens (oxides in wt.%, ratios in mol.%).

^aFe normalized: $Fe = Fe^{3+}/total Fe cations.$

	Calc-Alkaline Lamprophyres		AL	UML		
	Outer	Limits	Тур	ical		
	Minette Vogesite	Kersantite Spessartite	Minette Vogesite	Kersantite Spessartite		
Quartz	< 15	< 15	< 10	< 10		0
Leucite	< 25	0	0	0		
Nepheline	< 10	< 10	< 5	< 5	> 0	
Anorthite	< 25	< 30	< 15	< 10		
An number					No Restriction	
Albite						0
Orthoclase					< 20-25	0
Oligoclase					< 20-25	
Hypersthene						0
Chromite	< 5	< 5	0	0		0
Acmite	< 10	0	0	0		
Rutile	< 1	0	0	0		
Diopside	40-80	40-80	50-75	50-75		
Wollastonite	0 ^a	0 ^a	0 ^a	0 ^a	0	
Ak	0	0	0	0		
Ns (Na ₂ SiO ₃)	< 5	0	0	0		0
Ka (KAlSiO₄)	0	0	0	0		> 0
Ks (K ₂ SiO ₃)	0	0	0	0		0
La (Ca ₂ SiO ₄)	0	0	0	0		> 0
Perovskite	0	0	0	0		
Corundum					0	
Hematite					0	

Table C.6: Normative screens (analyses recalculated to 100% free of H₂O and CO₂; from Rock, 1977, 1984, 1986).

^aWollastonite is generally zero except where $CO_2 > 5$ wt.%.

C.3 Alkaline Lamprophyres

Alkaline lamprophyres are alkali basaltic or basanitic in composition, except for higher volatile contents (Rock, 1977). This group is composed of three rock types classified according to the mode and type of feldspars and feldspathoids. The classification scheme (from Rock, 1991) is given in Table C.7 and Figure C.1.

A chemical screen for this group of lamprophyres is presented in Table C.5, and the normative screen in Table C.6, together with those for the other two lamprophyre groups.

C.4 Ultramafic Lamprophyres

Ultramafic lamprophyres are associated with strongly alkaline rocks including carbonatites (Rock, 1991). Rock (1986) reviewed their characteristics, as a part of a global study of lamprophyres. In Rock (1986) he characterized this rare but widespread type of hypabyssal rock, and proposed a semi-quantitative classification of the five members of the group: aillikite, alnoite, damkjernite, ouachitite, and polzenite. This classification is based on light-coloured groundmass minerals and is presented in Table C.8.

Rock's (1986) review proposed modal, mineralogical, chemical, and normative screens for the ultramafic lamprophyres. The modal and mineralogical screens are given in Table C.9. The chemical screen can be found in Table C.5 and the normative screen in Table C.6.

Table C.7: Classification of alkaling	lamprophyres (from Rock,	1977).
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	Feldspars	Feldspars	No Feldspar
Olivine + Titanaugite + Amphibole (Barkevikite or Kaersutite)/Mica	Labradorite/Andesite > Alkali- Feldspar	Alkali-Feldspar > Plagioclase	
Na-Foids, No Leucite	Camptonite	Sannaite	Monchiquite


Figure C.1: Classification of alkaline lamprophyres and their volatile-poor and volatile-free equivalents (Rock, 1991).

Name	Melilite	Feldspathoids	Carbonates	Alkali-feldspars
Aillikite (common)	Absent	Absent	Essential	Absent
Alnoite (common)	Essential	Minor/Absent	Minor/Absent	Absent
Damkjernite (rare)	Absent	Minor/Essential	Essential	Minor
Ouachitite (rare)	Minor/Absent	Essential	Essential	Absent
Polzenite (rare)	Essential	Essential	Minor/Absent	Absent

Table C.8: Ultramafic lamprophyre classification (from Rock, 1986).

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Table C.9: Modal and mineralogical screens for ultramafic lamprophyres (from Rock, 1986).

Modal Screen (Minerals in Volume%)

Phlogopite + amphibole > 10 (typically > 25).

(2) Colour/mafic index > 67 (counting carbonates, melilite as mafic); typically > 67 and < 90.

(3) Absent minerals: diamond, fayalitic olivines, graphite, K-rich amphiboles, kaersutite, kalsilite, leucite/pseudoleucite, native metals, orthopyroxenes, pigeonite, plagioclase, primary muscovite, pyrope-rich garnet, quartz, (Na, K) silicates with (Zr, Nb, Ti, Ba; cossyrite, eudialyte).

(4) Alkali feldspar < 10, generally absent.

(5) Primary carbonates < 50.

Mineralogical Screen (Oxides in Weight%, Ratios and End-Members in Molecular%)

Olivine: Fo 78-92; MnO < 0.5, CaO up to 0.8.

Pyroxenes: Mg/(Mg + Fe) 70-95; Al₂O₃ < 13; TiO₂ < 6; Na₂O < 4; Si/Al 4-40.

Amphiboles: $K_2O < 3$; $Al_2O_3/TiO_2 < 5$.

Phlogopite: Mg/(Mg + Fe) 75-90; $8 < Al_2O_3 < 8$; BaO up to 12; TiO₂ up to 12.

Ilmenite: MgO 7.5; MnO up to 4; Cr₂O₃ 0.1.

Garnet: CaO > 25; Cr₂O₃ < 0.2; MgO < 3; FeO > 10; TiO₂ up to 14; ZrO₂ up to 20.

K-Feldspar: Or > 50; Fe₂O₃ < 2.

C.5 Minerals and Mineral Chemistry Diagnostic of the Lamprophyres in General

Lamprophyres contain minerals that can be found only in alkaline rocks; these include alkali pyriboles, Ba-Ti-phlogopites, Ba-K-feldspars, feldspathoids, melanitic garnet, melilite, monticellite, perovskite, and alkali silicates with transitional metals such as priderite (Rock, 1991). Mineral compositions can also be used to recognize lamprophyres collectively. Lamprophyres contain (from Rock, 1991):

- Calcic pyroxenes with Al₂O₃ > 10 wt.%. The only other rocks where this pyroxene composition can be found are metalimestones, lime-contaminated basalts, or occasionally mantle xenoliths.
- (2) Pyroxenes or amphiboles with $TiO_2 > 5$ wt.%, or phlogopites with $TiO_2 > 8$ wt.%.
- (3) High Ba amphiboles (BaO > 0.5 wt.%), phlogopites (BaO > 5 wt.%) and K-feldspars (BaO >2 wt.%).
 Phlogopites with high-Ba contents occur only in carbonatites and a few nepheline rocks, but are common in UML's.
- (4) High F amphiboles (with up to 4.1 wt.% F) and phlogopites (with up to 5.7 wt.% F).
- (5) Micas rich in Fe³⁺ are common in Al, CAL and UML rocks. They also occur in carbonatites. Micas rich in ferriannite are found almost exclusively in lamprophyres.
- (6) Mg-Fe-Sr-Ba carbonates occur only in carbonatites and lamprophyres.
- (7) High Zn spinels (ZnO and MnO both > 2 wt.%) and high Mg-Mn ilmenites (MgO > 5 wt.% or MnO > 2 wt.%)

(8) Sr-Ba apatites and Ca-Sr-Ba sulphates are common in lamprophyres.

C.5.1 Differences in Mineral Composition Between the Different Branches of the Lamprophyre Clan

Olivines in Al, CAL and UML rocks are slightly less magnesian (have a smaller mg number) than olivines in KIL and LIL rocks. They are also less well preserved.

Clinopyroxenes in LIL rocks have higher MgO/FeO ratios than those from UML, CAL, and AL lamprophyres. CAL clinopyroxenes usually have a higher SiO_2/TiO_2 ratio than do clinopyroxenes from AL, UML, and LIL rocks. Although there is overlap between the branches, AL pyroxenes are in general the most Al- and Ti-rich of the clan, while pyroxenes from LIL rocks are the most Al-poor.

Amphiboles in AL rocks are predominately kaersutite. Pargasite and hastingsite may also be present. Amphiboles are rare in UML rocks, but when present are predominately kaersutite followed by magnesio-hastingsite. CAL rocks contain Ca-amphiboles, usually hastingsite, tschermakite, magnesio-hornblende, and pargasite. Cognate primary amphiboles are absent in KIL rocks. LIL rocks contain sodic-calcic (richterite, katophorite) and alkali amphiboles (arfvedsonite, riebeckite, eckermannite) (Rock, 1991). The Si content of amphiboles in LIL rocks is significantly higher than for the other branches.

Discrimination between the lamprophyre micas is difficult except for LIL phlogopites which have low Al_2O_3 contents and low to high TiO₂ contents relative to AL, CAL and UML micas, and UML phlogopites which are often Ba-rich compared to phlogopites of the other branches.

Cognate, primary garnets occur only in UML rocks. These are Ca-rich, Mg-Mn-Cr-poor garnets, covering three main compositions: (1) and radite, (2) melanite with up to 20 wt.% TiO_2 , and (3) kimseyite with up to 19.5 wt.% ZrO_2 (Rock, 1991).

Plagioclases more calcic than albite are present only in camptonites, kersantites and spessartites, but albite itself occurs also in sannaites and in damkjernites (Rock, 1991). Plagioclase compositions range from $An_{0.5}$ to An_{90} .

Na-K-Ba feldspars are absent from KIL, UML (except damkjernites) and some LIL (fitzroyites, olivinelamproite) rocks. Minettes and vogesites (CAL) generally have a single K-feldspar: microcline, orthoclase, sanidine, occasionally microperthite, or in globular structures, anorthoclase or adularia. Kersantites and spessartites may conatin three feldspars: Na-feldspar, K-feldspar, and intermediate plagioclase. AL rocks contain two or three alkali feldspars (Ab+Or, Ab+Ao, Ab+Or+Ao). Damkjernites (UML) contain accessory, nearly pure orthoclase, albite-sodic oligoclase, or halophane. LIL rocks have only one feldspar, which is poor in Na and Ca and rich in Fe (Rock, 1991).

Feldspathoids occur in every branch except KIL. CAL rocks contain occasional minor analcime. AL and UML rocks commonly have analcime \pm nepheline \pm sodalite, but no leucite. LIL rocks may have leucite \pm minor analcime, but no nepheline (Rock, 1991).

Spinel compositional ranges overlap the different lamprophyre branches. However, a few conclusions can be drawn. CAL and AL spinels (and some groundmass UML spinels) belong to the magnetite-ulvöspinel series. Zn-rich spinels (with up to 8.7 wt.% ZnO) occur in CAL, AL and UML rocks, and are comparable to spinels found in Fe-Ni sulphide ores. LIL spinels overlap peridotite and kimberlite spinels. However, spinels are not often found in LIL, being incompatible with priderite. Spinels rich in both Mg and Mn

occur only in UML rocks. Spinels from UML rocks can sometimes lie within Mitchell's (1989) "trend 1" for kimberlites and lamproites.

Picroilmenite from UML rocks overlap with those in KIL rocks. Only the most Mg-rich picroilmenites (>13 wt.% MgO) are confined to KIL. Pure FeTiO₃, and relatively Mn-rich ilmenites are rare in KIL rocks relative to the other lamprophyres (Rock, 1991).

Perovskite is present only in KIL, LIL, and UML rocks. UML and LIL perovskites have MgO, MnO, Nb₂O₅, FeO and Na₂O contents higher than KIL perovskites.

C.6 Volatile-Poor Lamprophyre Relatives

Some anhydrous rocks have a geochemistry similar to some lamprophyres; their mineralogy is different due to the volatile-rich content of the lamprophyric magma. Table C.10, from Rock (1991), lists the volatile-free equivalents of some lamprophyres.

C.7 Comparison Between UML and Other Potassic Igneous Rocks

C.7.1 Comparison Between UML and Group II Kimberlites

There are major chemical differences between ultramafic lamprophyres and kimberlites. These are listed below, from Rock (1991):

UML's have lower whole rock SiO₂/Al₂O₃, MgO/CaO, Cr and Ni, but higher Zn, P₂O₅ and CO₂ contents, reflecting higher modal carbonates and apatite, but less olivine.

Class	Lamprophyre	Volatile-Free Equivalent(s)
CAL	Spessartite/Kersantite [Am, Pl, Af, Cpx, (Ol)]	Shoshonite/Absarokite [Pl, Af, Cpx, (Ol)]
AL	Camptonite [Am, Bi, Pl, Cpx, (Ol, Ne, Ac)]	(Ol)-Basalt, Basanite, Tephrite [Pf, Cpx, (Ol)]
	Monchiquite [Am, Bi, Cpx, Ne, Ac, (Ol)]	(Ol)-Nephelinite/Analcimite [Cpx, Ne, Ac, (Ol)]
	Sannaite [Am, Bi, Af, Pl, Cpx, Ne, Ac, (Ol)]	Mugearite [Af, Pl, Cpx, Ne, Ac, (Ol)]
UML	Alnoite [Bi, Cpx, Me, (Ol)]	(Ol)-Melilite [Cpx, Me(Ol)]
	Pozenite [Bi, Cpx, Ne, Me, (Ol)]	(Ol)-Melilite-Nephelinite [Cpx, Ne, Me, (Ol)]
KIL	Kimberlite [Ol, Bi, Cb, (Cpx)]	No Obvious Equivalent
LIL	Jumillite, Wyomingite [Bi, Am, Cpx, Lx, (Ol)]	(Ol)-Leucilite [Cpx, Lc, (Ol)]

Table C.10: Volatile-free equivalents of the various rock types (from Rock, 1991).

Ac = Acmite; Af = Alkali feldspar; Am = Amphibole; Bi = Biotite; Cb = Carbonate; Cpx = Clinpyroxene; Lc = Leucite; Me = Melilite; Ne = Nepheline; Ol = Olivine; Pl = Plagioclase.

(2) UML's have shallower REE profiles (lower La/Yb) at given enrichments.

- (3) Alkali feldspars, feldspathoids, Ti-Zr melanite, melilite, Mg-Fe-rich primary carbonates, and Na-Fe-Ti-Al-rich amphiboles are common in UML's but are absent in KIL rocks.
- (4) Olivine macrocrysts tend to be euhedral in UML's and rounded in KIL rocks.
- (5) UML pyroxenes have consistently higher Al_2O_3 and TiO_2 contents.
- (6) Some UML phlogopites have much higher TiO_2 values.
- (7) Some UML spinels follow different trends and are richer in Zn and Mn.
- (8) Some UML ilmenites are richer in Mn.
- (9) Some UML perovskites are richer in Na and Fe.
- C.7.2 Ultramafic Lamprophyres versus Melilitites and Related Rocks

The major differences between these two types of rocks are the following, according to Rock (1991):

- (1) UML's commonly have amphiboles and primary carbonates; melilitites do not.
- (2) UML's contain essential (>10 %) phlogopite, usually in two generations; melilitites generally contain only minor groundmass phlogopite.

- (3) UML's only vary rarely contain groundmass olivine or phenocryst melilite; melilities commonly contain two generations of both minerals.
- (4) UML's almost never form lavas; melilitites commonly do.

C.7.3 Ultramafic Lamprophyres versus Leucite-Bearing Ultramafic Rocks

Some leucite-bearing rocks show a similar paragenesis to UML rocks (olivine, pyroxene, phlogopite \pm nepheline \pm melilite). However, they contain leucite (absent in UML's) and/or kalsilite, and are higher in K₂O. UML's are usually associated with sodic alkaline rocks (carbonatites, ijolites, etc.) but not leucite-bearing ultramafic rocks (Rock, 1991).

C.8 Tectono-Magmatic Associations

Rock (1991) compiled lamprophyres according to their tectono-magmatic settings. Calc-alkaline lamprophyres are mainly found in convergent margins (Andean-type continental orogens, Greenstone belts, mobile belts, and island arcs) and in passive margins (transform faults). Alkaline and ultramafic lamprophyres are found in divergent margins (rifts and triple junctions) and intraplate settings such as ocean islands and hot spots. All branches of lamprophyre can be found on old or stable cratons (intraplate settings).

Calc-alkaline lamprophyres tend to occur with late to post-orogenic calc-alkaline (granitoid) intrusive/extrusive suites. They also occur with rocks of shoshonitic affinity such as monzonite, shoshonites, shonkinites, and syenites. Calc-alkaline lamprophyres can also be found contemporaneous with alkaline lamprophyres and no other igneous rocks. Alkaline lamprophyres are most commonly found

associated with mildly alkaline syenite-gabbro plutons or in areas affected by regional lamprophyric magmatism. In the latter case, they form dike swarms, sill complexes, and fields of pipes and diatremes. They can also occur with strongly alkaline suites, such as carbonatite-ijolite-nephelinite complexes. Only plagioclase-free alkaline lamprophyres (monchiquite and sannaite) occur in this setting, which is most characteristic of ultramafic lamprophyres. The great majority of ultramafic lamprophyres are intimately associated with carbonatites in continental rifts, either in lamprophyre-carbonatite dike swarms, nephelinite-carbonatite volcanoes, or intrusive carbonatite (ijolite-syenite, etc.) complexes (Rock, 1985). They also occur in isolation, as dike swarms or concentrations of plugs in both continental and oceanic settings (Rock, 1985).

Typically, calc-alkaline and alkaline lamprophyres form dikes or sills while ultramafic lamprophyres form pipes and vents (Rock, 1991).

APPENDIX D

SAMPLE DESCRIPTIONS

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S	DESCRIPTION	PETROGRAPHIC DESCRIPTION	DIAGRAM
	Red soft greasy clay. "Red gauge"; third layer outside the limestone. There is some brown rock in the bag.	What remains of this section is fairly thick and is composed of very fine-grained cloudy orange brown material. Impossible to identify any minerals. The matrix has a high birefringence (clays?). The section is colourless when thin.	
	Brick-red, soft. Second layer outside the limestone. Some green fragments. Chrome green alteration around fracture planes. Very schistose with slickensides. Greasier than Y-1.	Similar to Y-1. A few fibrous pleochroic crystals orange when vertical in the field and pale brown when horizontal (probably highly weathered biotite).	
9	Red and purple fragments with green spots (there was a sapphire in this sample).	 This section is ochre in colour and composed of clays, serpentine, carbonates, quartz and oxides. Serpentine replaces a prismatic mineral (pyroxene?). (a) Relics of igneous texture defined by subhedral prismatic colourless to pale yellow crystals (serpentine pseudomorphs) randomly distributed in a gray to brown groundmass composed of clays and carbonates (similar to Y-1 and Y-2). The section is patchy brown and gray with many large oxide patches. (b) Elongated colourless laths with very low birefringence. A noticeable feature of this section is the presence of prismatic gray features (< 0.1 mm), usually ellipsoidal, scattered through the light orange-brown areas. They are always rimmed by a brown orange mineral. (2) (a) High refringence, straight extinction. To the left of the large oxide patch, there is a strange mineral. It is colourless, has a high refractive index, low birefringence, and is shapeless. The grains are all broken up and slightly altered on their surfaces. 	(1) (2) (2) (2) (1)

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Ovvides	Clasts
This section is very fine grained to aphanitic and is composed mainly of carbonate. (a) Pyroxene relics, subhedral, white to pale yellow weathered to a colourless mineral with a very low birefringence (probably serpentine) and rimmed by an orange alteration (iddingsite?). (b) Fragment \sim 1 cm long with a different texture and completely weathered. The alteration minerals are uncertain (carbonates and micas?). The ubiquitous characteristic of this fragment is the texture which results from the presence of white hexagonal grains with brown ims scattered throughout the fragment. They are uniaxial and might be apatite relics. In crossed polars, the fragment a mosaic texture with grains smaller in the middle of the fragment. This fragment is similar to the highly weathered dike fragment found in red clays at the 4th of July claim (sample Y-16). It is inferred that this sample is highly weathered dike rock. (c) Breccia with \sim 0.5 mm patches of carbonates in a matrix of carbonates and clays.	There is very little material left from the original rock sample; a high proportion of the rock (the soft part) was ground away, leaving numerous holes. There is a well defined tectonic banding in the section. The pink fragments visible in hand specimen are very hard to see in thin section. (a) This area is yellow in colour and is composed of aphantic carbonates plus clays and serpentine. (b) The few small patches that remain from the grinding process are light brown to slightly orange in colour with a felty look. They are isotropic. (c) Very fine grained mineral with extremely high birefringence (black outline), white surface and patchy black (clays?). (d) << 0.1 mm laths with low birefringence in carbonates.
Yellow material.	Very schistose yellow, light green (serpentine?), and reddish rock.
Y-3c	Y-3d

Y-4	Light gray in colour with a light pink shade. At the contact with the diatreme.	Aphanitic limestone clasts (up to 3 mm), dark gray, irregular in shape set into a lighter gray fine grained carbonate matrix with a mosaic texture observable at $10\times$. The section is composed of 30 to 40% clasts and is cut by a vein of coarser (< 1 mm) calcite.
Y-5	Light gray, beige, and medium gray limestone fragments, found 1.5 m north of the diatreme contact.	Limestone, similar to Y-4. Clasts are smaller and less abundant (15 to 20%). More veins of secondary calcite.
Y-6b	Apple green altered ouachitite.	Light green in hand specimen. The section is composed mainly of carbonates, fine grained to aphanitic. It contains strongly deformed and weathered phlogopite grains throughout the dark gray carbonate groundmass as well as a few carbonatized and chloritized pyroxene. The phlogopite grains are light yellow to orange with black outlines and cleavages. There are some patchy light brown, brown, and colourless areas in the section. Composition unknown.
Y-7	Beige limestone fragment with a dark-gray to black inside rim (~1 mm) and a serpentine outside rim. Probed dark rim and serpentine.	Limestone. It contains large areas (\sim 30% of the section) of coarser grains (\sim 0.3 mm) in an aphanitic matrix.

Y-8a		N N N N N N N N N N N N N N N N N N N
Contact between limestone and diatreme? The two sections are very fine grained with diffuse patches of coarser material (talc? micas?) Area (a) shows a foliation defined by orange brown and brown bands (composed of clays?). Area (b) is cream to tan in colour and aphanitic. There are some calcite crystals (< 0.2 mm long) that have crystallized perpendicular to the foliation shown in area (a). In section Y-8a there is also approximately 10% orange patches composed of grains less than 0.1 mm. Fragments from section (a) are scattered along the contact between the two rock types. (b) is dark gray to colourless and might be composed mainly of talc. (c) Limestone fragments (same as Y-7).	 (1) (a) Limestone breccia with a few biotiteotite grains (< 1 mm). (b) Brick-red fragment with relic of an igneous texture (weathered dike fragment?). Composed of serpentine plus carbonates plus oxides. (2) (a) Small angular dike fragment? Phlogopite is scattered around the fragment but there is no trace of phlogopite in the fragment itself. (b) Aphanitic limestone clast (3 cm long) in limestone breccia containing a few biotite grains (< 1 mm long). 	Section fairly weathered. Matrix cloudy. Phlogopite has locally a greenish rim and oxides along cleavages. Globular structures composed of serpentine, oxides and carbonates present. Pyroxene are slightly to highly (up to 50%) uralitized. (b) 6 mm pyroxene section with core and uralitized rim. Ocellus with green prisms of acmite plus minor carbonates.
Limestone clast in diatreme (?) with a pink, purplish pink, yellow and light gray rim of clay. Two polished sections of the contact.	Yellow breccia with limestone, siltstone and lamprophyre clasts. Contact metamorphism between breccia and clasts. Two polished sections.	Light green and purplish crystal with hematite-red rim, pseudo- hexagonal.
Y-8a Y-8b	Y-9 (2)	Y- 11a-1

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Table D.1: (Petrographic descriptions of polished thin sections from the Yogo dike) continued.

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Section fairly weathered, more than Y-11a-1. (a) Large carbonates plus quartz plus serpentine xenolith. Two mm clinopyroxenites, patchy. Ocellus (< 2 mm) composed only of analcime. High carbonate content in the matrix. Some pyroxene are biotitized (25% of their surface), while phlogopite is often completely chloritized with oxides along cleavage planes. Some phlogopite grains are carbonatized. locally chloritized and discoloured. Some pyroxene are uralitized.		(a), (b), (c) Fluid inclusions found in pyroxene megacrysts; might be secondary. (c) In the first biotite pyroxene at the left of the crack (right on the polished section) there is a row of what looks like fluid inclusions parallel to the crystal growth zones. (d) White mica, colourless with oblique extinction.
	Five mm sapphire in matrix (cut).	Small black spheres with metallic look, 1 to 6 mm diameter with calcite? core.
Y- 11a-2	Y-11- b	Y- 12a

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(a) There are many ocelli on the section (filled circle). They show interesting zoning; one side of the ocelli is composed of carbonates while the other contains green acmite, analcime and opaques. (b) Carbonatized and biotiteotized pyroxene with adjacent secondary phlogopite. (c) Large green pleonaste spinel plus magnetite in matrix. (d) Phlogopite megacryst (1 mm) with pleonaste spinel on top (no magnetite). (e) Phlogopite \pm pyroxene glomerocryst. Phlogopite is exsolving opaques along cleavage planes and some cubes of chrome spinel. One phlogopite has a light green (chlorite?) grain on top of it. Pyroxene is not weathered. (f) Pleonaste spinel-magnetite on weathered pyroxene. (g) 2 mm long xenolith with pyroxene and many pleonaste spinel. Secondary biotite (or phlogopite) associated with pleonaste spinel. The autolith is composed of 70% pyroxene and 30% phlogopite. Phlogopite has pyroxene inclusions and is fresh. Pyroxenes are locally poiklitic with secondary biotite and slightly carbonatized (< 25%). The matrix. Some areas of the autolith are interfingering with the dike rock.	(a) Sapphire; (b) ocellus; (c) ? (d) ?	(a) 5×4 mm ocellus (carbonates in centre, analcime in border). (b) 1 cm globule attached to the ocellus (a) and composed of analcime \pm carbonates + acmite, secondary chlorite, and oxide. Some oxides are elongated. (c) Large (1 cm) carbonates + quartz + serpentine + chrome spinel xenolith rimmed by pyroxene grains. (d) Pleonaste spinel-clinopyroxenite.
Black spheres with white cores (ocelli).	1 cm long greenish and reddish xenolith.	Ocelli and pear shaped greenish- red xenolith with red and green rim.
Y- 12b	Y- 12c	Y- 12d

Y- 12e	1 cm round patchy light to medium green xenolith.	(1) Clinopyroxene partially weathered to carbonates in a globular feature. (2) Clinopyroxenite. (3) Ocellus composed of carbonates \pm barite core with an analcime rim. (4) ? (5) Pyroxene pseudomorph?	5 00 4 00 3 0
Y-13	Similar to Y-11, hexagonal greenish crystal with a hematitered rim.	(a) Vein of green highly birefringent mineral with carbonates and a few opaques. (b) Large (5 mm) pyroxene. (c) Xenolith composed of carbonates + serpentine + quartz \pm oxides rimmed by acmite and oxides. Two small features (hexagonal in shape) around the xenolith. (d) 2 mm pyroxene cross-section.	1 the c
Y-15	Very soft breccia with reddish brown, white, pink and green fragments. It is said that it is possible to find sapphire in this rock.	Breccia with a few 0.5 mm limestone fragments and some red-brown clasts in gray aphanitic matrix composed of carbonates. Impossible to identify anything else.	
Y-16	Strongly weathered dike? fragment, found in the brick-red breccia. South of the pool.	Highly weathered dike fragment. Only phlogopite is still recognizable, but highly altered. It is in a cloudy matrix (carbonates?).	
Y-17	Breccia with mainly limestone fragments; some dike fragments. Same location as Y-16.	Breccia composed of red-brown < 2 mm fragments in a fine grained to aphanitic matrix composed of carbonates + red alteration + quartz. There is also a few limestone fragments and two quartz + carbonate + red matrix clasts, 2 mm long. Dike fragments were not found in this section.	
Y- 18a	Brick-red rock with green and yellow spots (clasts?). Also yellow clay. East (?) of Yogo Creek. Found a sapphire (S- 18a).	The section is medium brown to dark brown, cloudy, aphanitic, composed mainly of carbonates with a few phlogopite grains. Impossible to identify anything else.	

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Dike fragment 1.5 cm across completely altered except for a few phlogopite grains, highly altered but still recognizable.	 (1) (a) 8 mm long dike fragment (?) with igneous texture relic defined by 0.5 mm long prismatic orange pseudomorphs in carbonates. The rest of the section is composed of very fine grained to aphanitic carbonates with a few phlogopite grains (< 0.5 mm) scattered throughout it. (2) Same as (1) with coarser carbonates and more phlogopite remnants. 	Many highly zoned pyroxene and phlogopite megacrysts. Some are carbonatized and biotitized. (a) 12 mm long carbonates + serpentine + chrome spinel pseudomorph. Biotite in fractures. Unweathered area in the center of the crystal. (b) 3 mm long diopside.	Polish not good. One half of the section has a sapphire with spinel rim. (a) Quartz-carbonates-sphene xenolith (+ weathered phlogopite and pyroxene inside). Na-rich alteration around xenolith. Some pyroxenes have interesting rims. 5 mm pyroxene megacryst on the opposite side of the section number.	Pyroxenes and phlogopites with good zoning, especially for megacrysts. (a) Carbonatized xenolith.	Highly weathered section. Phlogopite grains in brown cloudy matrix. Fuschite alteration scattered throughout the section.
Green and purplish-red fragments with large green areas. 60% of the rock is gone due to grinding.	Greenish soft rock grading into brick-red facies. Green weathered areas have some micas.	Fairly fresh; with diopside phenocryst. 5 mm \times 1 cm diopside phenocryst (?) with a hematite rim.	Fairly fresh. 1 cm sphere with light gray and yellow patches and a green rim. Same rock as Y-21 and Y-22.	Green xeno-phenocrysts. Same boulder as Y-21 and Y-22.	Completely weathered medium green ouachitite.
Y- 18b	Y-19 (2)	Y-21	Y- 23a	Y- 23b	Y-24

quatrz+carbonates	V V	Clinopyroxenite
Carbonatized phlogopite-clinopyroxenite with secondary chrome spinel. Many strongly zoned pyroxenes [(a) 11 rims, (b) 5 rims]. One (c) may have exsolution bands. (d) Transition between chlorite and spinel?	Phlogopite-clinopyroxenite. Pyroxene with interesting zoning (the core seems to have a very different composition based on extinction angles). Few orthopyroxene? Pyroxene and phlogopite of the autolith unzoned except where in contact with the dike magma. Pleonaste spinel on phlogopite.	Phlogopite-clinopyroxenite highly weathered (carbonatized + biotitized) on 25 to 50% of its surface. The phlogopite phenocrysts (6 to 7 mm) are mainly weathered along their cleavages. They have numerous carbonate patches (square to rectangular). (a) Phlogopite + pyroxene glomerocryst probably coming from the phlogopite-clinopyroxenite. It has carbonates + serpentine + quartz alteration probably after pyroxene. One pyroxene has around 15 zones in the area of (a). Intense biotitization of the groundmass.
Fairly fresh; many xeno- phenocrysts. 2 cm × 1 cm transparent smoky xenolith.	3 cm green irregular xenolith.	2 cm long light green to pistachio green xenolith with black prismatic mineral (augite).
Y- 25a	Y- 25b	Y- 25c

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Some of the pyroxenes have good zoning but nothing exceptional. 6 mm ocellus composed of analcime. (a) Pleonaste spinel-magnetite-pyroxene in matrix. (b) Pleonaste spinel on big patchy pyroxene, almost no magnetite rim on pleonaste spinel. Pyroxene altered to carbonates + quartz on 25 to 40% of its surface. The fresh core (around 1 mm across) shows opaque exsolution along the crystal cleavages and numerous small fluid inclusions. No biotite on this pyroxene. (c) Pyroxene to biotite to magnetite + pleonaste spinel (visible but small at $2.5x$). (d) Pleonaste spinel + magnetite on phlogopite next to a phlogopite megacryst. (e) 2 mm pyroxene slightly (10%) carbonatized. (f) Good ocellus composed of carbonates + analcime and acmite rim. (g) Good green pleonaste spinel with mag rim on pyroxene. (h) Pleonaste spinel with magnetite rim and biotite between the two next to a 1 mm pyroxene. (i)(k) 2 mm pyroxene. (l) 3 mm pyroxene.
Transparent sphere with rim.
Y- 25d

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 (a) Chrome spinel associated with pyroxene and phlogopite. In the same area, clinopyroxenite with pleonaste spinel rimmed by magnetite. There is some biotite between the pleonaste spinel and the magnetite rim. The pyroxenes of the clinopyroxenite are highly carbonatized with some clear isotropic material. One of the pleonaste spinels is on a pyroxene. (b) Pleonaste spinel rimmed by magnetite in matrix, adjacent to a pyroxene. (c) Chrome spinel on pyroxene. (d) This large pyroxene (1 mm) has 11 rims and is highly biotitized. Biotite forms polikilitic areas. There is an isotropic white grain in the middle of the pyroxene. (e) Carbonates + serpentine + chrome spinel pseudomorph. (f) Large (2 mm) pyroxene slightly (15 to 20%) biotitized and carbonatized. Biotite is green (chlorite?). (g) Large (3 mm) pyroxene. 	Secondary biotite abundant in this section. Good zoning of the pyroxene and phlogopite with good examples of resorbed cores. The secondary biotite is easy to distinguish from primary material. The latter occurs as mantle of phlogopite megacrysts and as microphenocrysts while the secondary biotite occurs as polkilitic masses interstitial to pyroxene and phlogopite, englobing matrix pyroxene, and apatite. It also occurs on pyroxene megacrysts associated with carbonates.
Yellowish xenocryst with a hematite-red rim.	
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(a) 1.5 mm pyroxene megacryst, gray, partially resorbed. In the same area there is pleonaste spinel rimmed by magnetite. There are many 1 to 2 mm pyroxene in this area. (b) Green pleonaste spinel forming on phlogopite (hard to find). (c) Pleonaste spinel with magnetite rim and biotite between the two. (d) Highly weathered 3 mm clinopyroxemite with green pleonaste spinel thinly rimmed by magnetite. Pale orange to green biotite (?) alteration on pyroxene. Pleonaste spinel seems to be associated with this alteration. (e) Hexagonal carbonates + quartz + chrome spinel + serpentine + pyroxene remnant rimmed by phlogopite and pyroxene (1 mm). The phlogopite surrounding the carbonates pleonates spinel (0.1 mm) on weathered pyroxene.	 (a) Dike fragment? composed of serpentine and iron oxides. It has a strong foliation. (b) Limestone clasts and quartz fragments (0.5 mm). (c) Composed of very fine grained clays (?), serpentine, oxides and orange staining. 	Weathered section. pyroxene and phlogopite with good zoning. Large (1 cm) clinopyroxenite with pyroxene (0.5 to 1.5 mm), slightly zoned. One pyroxene from the clinopyroxenite has a chlorite crystal on top of it. Outside the clinopyroxenite autolith the matrix is biotitized (green). carbonates + quartz + serpentine xenolith. Phlogopite in the section is partially altered.
Similar to 25e.	Yellow, soft diatreme with very light green patches. Not very greasy. Mainly limestone fragments.	Abundant pyroxenes and green xenoliths. 1 cm light green pyroxene with medium green rim. Fluid inclusions?
Y-25f	Y-29	Y- 31a

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Partially altered section. (a) 9 mm sub-hexagonal carbonates + serpentine + quartz. (b) On the side of the section, pleonaste spinel growing on phlogopite (excellent). (c) Very fine grained (<< 0.05 mm) clinopyroxenite (1 mm across); recrystallized. (d) Pleonaste spinel. In the same area, 3 mm highly carbonatized pyroxene. (e) Pyroxene in ink circle has excellent zoning but it is too weathered (carbonates \pm biotite) to be analyzed. (f) 4 mm long, prismatic pyroxene glomerocryst. pyroxene are uralitized and carbonatized. The glomerocryst was probably a single crystal before. There is one pleonaste spinel on top of one of the pyroxene. Good zoning of the pyroxene in general in this section. Four ocelli of 3 mm. One is composed of carbonates and acmite. Two are composed of analcime, carbonates and acmite.	1 cm serpentinized megacryst with island of the original mineral. Distinct zoning on many pyroxene.	(a) Pseudo pleonaste spinel with magnetite rim in matrix. (b) Large (1 cm) pyroxene pseudomorph highly carbonatized with minor biotite. (c) Weathered phlogopite-clinopyroxenite with pseudo pleonaste spinel. Pyroxenes have a cloudy alteration and minor carbonates (uralitized). Grains are unzoned except at the border of the autolith. Locally, edges are green with included opaques. Green pleonaste spinels are grewing there. (d) 2 mm clinopyroxenite, fresh. In the section, there are many altered patchy pyroxene megacrysts and a few fresh ones. Phlogopite megacrysts are slightly altered.	(a) Pleonaste spinel-clinopyroxenite with equigranular texture (pleonaste spinel seems to be growing on or near the pyroxenes). There might be some amphiboles too. Magnetite rim around pleonaste spinel.
Pseudo-hexagonal yellow crystal with hematite-red rim.	Medium green pyroxene (diopside?) 1.2 cm long.	Sapphire in green xenolith.	Plagioclase xenocryst?
Y- 31b	Y- 31c	Y- 31d	Y- 31e

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Excellent zoning of the pyroxene. Some are fairly weathered (carbonatized in cracks). (a) Clinopyroxenite (1 cm) with partially carbonatized and biotitized pyroxenes, locally serpentinized. (b) 5 mm carbonates + chrome spinel megacryst, pseudomorph after pyroxene? (c) Strongly zoned pyroxene with carbonatized cores. (d) Big pleonaste spinel (0.5 mm) in matrix, in contact with green interstitial chlorite. In the same area, 3 mm hexagonal crystal weathered to carbonates + serpentine + quartz + chrome spinel. (e) Slightly weathered (carbonates + discoloured cleavages) phlogopite (1 mm) core with biotite rim. It has a small pleonaste spinel on top with very thin magnetite rim. There is a lot of proto-spinel in this section. They are mainly associated with the matrix. Magnetite rim in matrix with beginning of pleonaste spinel in the middle. Proto-spinel is associated with green to brown biotite. This mica is interstitial and seems to be after the matrix. (f) 2 mm pyroxene with core partially weathered to carbonates and biotite. The biotite is polkilitic. (g) 2 mm carbonates + serpentine + chrome spinel megacryst.	a few phlogopite megacrysts (2 mm).
1 cm dark green pyroxene.	
Y-31f	

(a) 3 mm good pleonaste spinel-clinopyroxenite with 15% spinel. Pleonaste spinel is interstitial to pyroxene or on top of pyroxene. Pyroxenes are carbonatized and slightly biotitized plus an isotropic white mineral. Magnetite rims are very thin to nonexistent around pleonaste spinel found inside the xenolith. When pleonaste spinel is in contact with the dike matrix or phlogopite from the dike, the magnetite rim is thicker. The matrix of the xenolith is highly biotitized. (b) Unusual pyroxene strongly zoned with resorbed areas; its core is composed of pyroxene, phlogopite phenocrysts in a groundmass of oxides, apatite (?) needles and analcime. (c) 8 mm pyroxene slightly carbonatized (10 to 15%). (d) 6 mm ocellus composed of carbonates in the center and analcime \pm acmite at the border. Touching it is a 3 mm analcime \pm carbonates + acmite + oxides. (f) 1 cm phlogopite- clinopyroxenite.	 (a) 6 mm clinopyroxenite composed of 2 mm unzoned, almost fresh pyroxene. (b) Chlorite + biotite + carbonates (proto-spinel?) on pyroxene. (c) Chlorite on biotite. (d) 1 mm ocelli composed of carbonates in the centre nimmed by amphiboles. (e) Chlorite with opaque rim on phlogopite. Cloudy mineral inside chlorite. (f) Pleonaste spinel on phlogopite (no magnetite rim). (g) Magnetite-chlorite in matrix adjacent to biotite. (h) Triangular chlorite (0.1 mm) on weathered pyroxene. (i) Pyroxene megacryst with magnetite-chlorite nearby. On the pyroxene. The pyroxene is white (not yellow), very slightly weathered (tiny needles). (j) Chlorite on biotite. (k) Pleonaste spinel on biotite, chlorite abundant around. A triangle is weathered to chlorite, chlorite abundant around. A triangle is weathered to chlorite. (n) 0.1 mm pleonaste spinel on phlogopite (no magnetite rim).
1 cm rimmed pyroxene with a dark green core.	Dark green pyroxene like 31f.
Ч- 31g	۲- 31h

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3 c Pyr	m long bluish-green xenolith? oxene phenocryst with a nter rim.	(a) Chrome spinel. (b) Sapphire. (c) Pyroxene. (d) Pyroxene. (e) Pleonaste spinel. There is a Cr-spinel-pyroxene xenolith close to the big pyroxene and sapphire.	
2 cm × 1 xenolith.	cm apple green	3 pleonaste spinel xenoliths. (a) 1 mm clinopyroxemite. Pyroxenes are completely carbonatized. Some pleonaste spinel are not isotropic. (b) 1 mm clinopyroxemite autolith. (c) 3 mm clinopyroxemite. Pyroxenes are carbonatized. No magnetite rim around the spinel that is inside the pyroxene; the pleonaste spinels outside the pyroxene have a magnetite rim. Just outside the green ink circle there is a pleonaste spinel- magnetite and a light yellow mineral between the pleonaste spinel and the magnetite. (d) Pleonaste spinel-magnetite in carbonatized matrix. (e) Phlogopite-clinopyroxenite, highly weathered. Islands of pyroxene and highly weathered phlogopite in a sea of carbonates + serpentine + quartz + chrome spinel. Pyroxenes are 0.5 to 2 mm and phlogopites 0.5 mm. (f) Cloudy ocelli (2 mm) composed of analcime + acmite \pm carbonates.	DE AO B+Serp+Qtz+weathered PH
Light gre as 31k.	en pyroxene; same rock	Good phlogopite megacrysts. Pyroxenes have good zoning but nothing too spectacular. One pyroxene with carbonates + pyroxene + phlogopite in its core. (a) Chloritized and biotitized pyroxene. In the same area, there are good pyroxene sections 0.5 to 1 mm across. (b) 0.5 mm phlogopite megacryst. Next to it, there is a pleonaste spinel + magnetite + chlorite in matrix. (c) Magnetite \pm chlorite. (d) Pleonaste spinel (0.1 mm) on phlogopite megacryst (no magnetite rim). (e) 1 cm phlogopite-clinopyroxenite partially carbonatized + cloudy mineral (serpentine + chlorite). (f) 2 mm ocelli composed of carbonates in the middle and analcime \pm carbonates \pm acmite at its border. Ocelli are abundant in this section.	

Y-311	2.5 × 1.5 cm apple green xenolith.	(a) Two pyroxenes with good zoning (square core). One has an epidote grain on it. (b) Phlogopite-clinopyroxenite). It has a similar mineralogy to the dike, pyroxene and phlogopite in amorphous matrix. The phlogopite content is less than the one of the dike. The matrix is isotropic dark gray compared to brown for the dike, this could be due to alteration. The texture of the autolith is equigranular. The pyroxene phlenocrysts are about two times the size of the pyroxene in the matrix of the autolith. Some grains are completely weathered to serpentine. Pyroxenes are usually not zoned. There are very few opaques in this xenolith. There is a large chrome spinel on the lower left side of the autolith. There is a large chrome spinel on the lower left side of the autolith. It is surrounded by a green pleonaste spinel with magnetite. Pyroxenes are usually not zoned. There are very few opaques in this xenolith. There is a large chrome spinel on the lower left side of the autolith. It is surrounded by a green pleonaste spinel with magnetite. Pyroxenes are 1 to 2 mm. Just to the side of this autolith. (f) Pleonaste spinel-magnetite surrounded by wavy orange purple-green isotropic material on phlogopite. (g) Thme pseudomorphs?). There is also a 1 mm pyroxenes are around 2 mm and are carbonatized and septinel-magnetic surrounded by wavy orange purple-green isotropic material on phlogopite. (g) Clinopyroxenite with 0.2 mm lon pyroxene with a few phlogopite and chrome spinel Pyroxenes in the middle with analoine at their border. The texture of this section is different. The phlogopite and chrome spinel grains. There are 2 small (1 mm) ocelli composed of carbonates in the middle with analcime at their border.	OH OH OH OH OH
		microphenocrysts are all about the same size and distributed evenly throughout the section without any particular orientation.	
Y- 31m	Sapphire		

Strongly weathered. Secondary biotite and chlorite abundant. Pyroxenes are highly uralitized. The matrix is very cloudy. 15% of the surface of the section is composed of ocelli. They are composed mainly of carbonates with minor analcime in their rims. Some have a few acmite crystals associated with analcime. (a) Good phlogopite megacryst (0.5 mm). No pleonaste spinel on this section.	
Ouachitite with white ocelli, average 1 mm in diameter, up to 5 mm, form approximately 25% of the rock.	Strange xenocrysts. 2.5 cm elongated xenocryst with < 1 mm black mineral. Sapphire.
Y-32	Y- 33a

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Y- 35a	Xeno-phenocrysts. Ocellus? or xeno-phenocryst with light smoky colour, transparent, pear shaped.	This section also has globular features with oxide rims. (a) Carbonates + pyroxenes (diopside pseudomorph?). (b) 3 mm ocellus with coarse grained calcite. There are two other ocelli of this type on the section. (c) Good pyroxene section, 1.5 mm across. Many weathered pyroxenes.	A O B
Y- 35c	Sapphire?	 (a) 2 mm phlogopite-clinopyroxenite with partially weathered pyroxene and phlogopite. (b) There are 2 large (2 to 3 mm) opaque glomerocrysts (+ carbonates); they are surrounded by green chlorite. (c) Pyroxene megacryst, 4 mm. Excellent pyroxene megacrysts, 2 to 3 mm, rim altered but core usually fresh. 	$A^{O}_{CO}(0)$
Y-36	Yellow brownish and some gray. Not as greasy as Kelly Coulee diatreme. Flow patterns.	(a) Mosaic of equigranular carbonates < 0.1 mm in size. (b) Banded carbonates.	B
Y-40	Brecciated limestone with dike? matrix.	Aphanitic 1.5 cm angular limestone fragments, quartz fragments and serpentinized clasts (< 3 mm) in a matrix of aphanitic carbonates.	
Y-41	Brecciated limestone with dike? matrix. 3350° west of Yogo Creek, 500° up the 35° slope.		

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Large (2 cm long) clinopyroxemite with fairly fresh 0.5 to 2 mm pyroxeme. The pyroxeme cores are partially weathered to carbonates and an isotropic cloudy grayish mineral. (a) 2 mm isotropic globular structure with pyroxene remnants and chrome spinel in the middle. A phlogopite megacryst by this globule has a large (0.1 mm) green spinel on it. (b) Good zoning of a pyroxene megacryst (0.5 mm). This is adjacent to a globular structure composed of clear, colourless isotropic mineral + carbonates + serpentine + chrome spinel. (c) Large pleonaste spinel-magnetite surrounded by an unknown mineral after phlogopite. (d) Strongly weathered clinopyroxenite (2 mm) composed of 0.5 mm pyroxene. The clinopyroxenite hosts a green pleonaste spinel.	(a) Isotropic globular structures with same alteration as the matrix. (b) Pleonaste spinel-magnetite on pyroxene. There is a colourless isotropic mineral surrounding the magnetite rim. There is nothing at the center of magnetite. (c) There is very little left of an apple green xenolith. It looks similar to the 31L xenolith. (d) Ocellus (2 mm) composed of analcime, amphiboles and \pm carbonates. (e) 2 mm phlogopite-clinopyroxenite; phlogopite grains are highly weathered. The matrix of this section is highly weathered by a cloudy isotropic mineral.	Interesting section. (a) Large (8 mm) green clinopyroxene megacryst similar to Y-12a. The rim is amphibolized. (b) Highly carbonatized xenolith containing phlogopite remnants, fibrous and discoloured. There are also some pyroxenes locally weathered to an isotropic gray mineral. Some large pyroxenes (1.5 mm) are fresh. (c) Pleonaste spinel (0.2 mm)-magnetite on phlogopite. (d) Pleonaste spinel (0.2 mm)-magnetite associated with biotite in matrix. (e) 2 mm fresh pyroxene. (f) Good phlogopite megacryst for probe analysis. Ocelli (0.5 mm) composed of carbonates with a rim of amphibole (0.5 to 1 mm).
Moderately weathered, with pyroxene xeno-phenocrysts.	Apple green xeno-phenocryst.	Yellowish irregular 1 cm long fragment. Black, 1 cm transparent xeno?-phenocryst? From around the pond at the American Mine. Probably from the Middle Mine.
Y- 42a	Y- 42b	Y- 42c

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Table

The texture is strongly obliterate; the phlogopites are almost completely converted to biotite, discoloured, brown with patchy light orange, oxides in some cleavages and locally hosting needle like crystals colourless with a high birefringence. The pyroxene phenocrysts are partially to highly converted to epidote. The matrix is highly weathered to a cloudy brown and gray unknown mineral. Scattered throughout the matrix are prismatic dark gray fine grained isotropic patches usually hosting prismatic apatite (?) and composed of serpentine + clays + phlogopite pseudomorphs. Protolith unknown. Dark green acmite in the matrix.	Shows same texture and alteration as 43a but not as weathered. (a) Large pyroxene with dark gray isotropic patches. (b) 3 mm fresh pyroxene megacryst.
Strongly weathered in hand specimen. Yellowish olive-green to medium dark green in colour. Around the washing pond; probably from the Middle Mine. Crumbles easily.	
Y- 43a	Y- 43b

Xenolith E B O 0 C B O 0 D 0 0		
This section is fairly weathered. The colourless pyroxenes (diopside) are cloudy on about 15 to 50% of their surface. For the light green pyroxene (augite) it is even more (50 to 75%). The phlogopite megacrysts are slightly altered. Secondary biotite is abundant on the sections. It seems that the gray isotropic mineral observed on section 43a is after the light green augitic pyroxenes. (a) 3 mm ocellus composed of cloudy analcime \pm carbonates + acicular green acmite. (b) 8 mm phlogopite-clinopyroxenite completely weathered. Pleonaste spinel in the clinopyroxenite are weathered yellow. (c) 1 mm ocellus same as (a) but with some secondary biotite and a lot of acmite. (d) 1 mm ocellus with a carbonate core and analcime \pm carbonates \pm acmiterim. There are also some small (< 1 mm) carbonates coelli on the section. (e) 3 mm phlogopite-glomerocryst; phlogopite grains are 0.5 to 1 mm long.	Garmet-clinopyroxene-plagioclase granulite xenolith. Garmets are < 0.5 mm across including a thick kelyphitic rim. Some garmets are completely kelyphitized. Clinopyroxenes are < 0.3 mm, and interstitial to garmets. A few plagioclase grains < 0.2 mm were found, also interstitial.	
Moderately weathered with black xenoliths and 5 to 7% ocelli. Also 3% apple green xenoliths and some < 5 mm rusty patches. From the English Mine.		
Y- 44a (2)		

Y-	Dark green to black xenolith.	1 to 1.5 cm by 5 cm long xenolith composed of brown amphibole,	
44b)	clinopyroxene, phlogopite, pyrite, and pleonaste. Amphiboles form $\sim 80\%$ of the xenolith and are coarse grained (0.25 to 2 mm), subhedral to enhedral dark brown and strongly pleochroic. Clinopyroxene is the	Xenolith 235
		second most abundant mineral in this xenolith. Grains are strongly to	
		pyroxenes are in a cloudy matrix forming 5 to 10% of the section. The	
		dark gray and black. It is included or on top of pyroxene when these are abundant and interstitial to or included in amphiboles when these	
		are the main mineral of the area. Many opaques are secondary. The	
		xenolith is heterogeneous. Some patches are rich in opaques (25 to 30%) and pvroxenes (~50%, sometimes less) with only 20 to 50%	
		amphiboles. The contact between the xenolith and the dike is complex with numerous embayments. It is difficult to differentiate what helonos	
		to the xenolith and to the dike.	
		(1) Partially amphibolized pyroxene. (2) $?$ (3) 0.2 to 0.5 mm pleonaste	
		spinel on pyroxene. (4) Phlogopite in amphibole grains. (5) Weathered pyroxene.	
Y-45	Yellow-brown diatreme with	Limestone breccia composed of fine grained to aphanitic carbonates and	
	limestone clasts; very similar to Kelly Coulee rock, but not as	orange iron oxide stains.	
	soft. Not in place; around the		
	eastern pit of the English Mille workings.		

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Idish-brown rock; allFine grained (< 0.1 mm) immature limestone with quartz clasts.	 k gray to black limestone. Highly to completely weathered dike fragments (< 7 mm) and limestone by e some dike sand in the fragments. There is an unidentified mineral in the matrix. It is South wall of the English , just before the bridge at the piotiterefringence (white to black) extinction at 45°. Some grains are pest part of the second at slightly more than 90°. 	angly weathered. Grayish- on velowish-green in bur. North wall of EnglishVery similar to Y-43. Higher content of acmite (?). Compared to Y- acmite (?). Compared to Y- 43, there are no pyroxene megacrysts of the non-patchy type. Pyroxene bur. North wall of EnglishVery similar to Y-43. Higher content of acmite (?). Compared to Y- 43, there are no pyroxene megacrysts of the non-patchy type. Pyroxene are converted to a cloudy alteration with serpentine. Phlogopite is weathered (discoloured) and locally altered to fuschite. The matrix is cloudy and composed of carbonates, clays and perhaps micas.		m small pit east of EnglishVery weathered to carbonates. Phlogopite is still recognizable. The (west of Y-45). One piece(west of Y-45). One piecesection is similar in look to the weathered dike fragments of section Y- 47, but is a little bit less weathered.w strongly weathered47, but is a little bit less weathered.chittle in contact with reme. Another is fairlyh, except for calcite veins.
Reddish-brov crumbled, fo grained sand pebbles. Ab eastern end o 10" chip sam wall. Simila breccia, but v	Dark gray to Maybe some bag. South v Cut, just befo deepest part trench. 6" ch	Strongly wea green to yellc colour. Nort Cut, before o		From small p Cut (west of shows strong ouachitite in diatreme. Ar fresh, except
Y-46	Y-47	Y- 48a	Y- 48b	Y-49

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Matrix completely cloudy. "Patchy" type pyroxene (augite) highly weathered. Other pyroxene (colourless to very light yellow diopside) slightly to moderately (< 25%) weathered. The center of magnetite grains is carbonatized as well as the matrix. Phlogopite is slightly to moderately weathered, locally green. (a) Green chlorite (?) on phlogopite with cloudy hexagonal crystal inclusion (leucite, nepheline pseudomorphs? or apatite). (b) Same as (a) but fresh. (c) Cr-spinel. There is no pleonaste spinel in this section (weathered?).	The only things still recognizable are the phlogopite crystals but they are strongly weathered. Everything else is cloudy.	A few dike fragments completely carbonatized with phlogopite remnants. There are some phlogopite megacrysts scattered throughout the matrix between the fragments. Also some red, subangular quartz-bearing clasts (0.1 to 0.2 mm).	Upper crust xenolith 2 cm in diameter. It is patchy white, green, cream, light brown. It has a spinifex-like texture due by radiating feldspar laths. Islands of quartz surrounded by a sea of feldspars. Quartz is always rimmed. The plagioclase crystals are in a very fine grained matrix of plagioclase feldspar, quartz and carbonates. (a) Quartz with fluid inclusions. (b) Feldspar. Feldspars have only a Carlsbad macle. Weathered pyroxene of the "patchy" type. Ocelli.
Fairly fresh ouachitite. From the Jim McCauley claim.	The dike fragments. are strongly weathered. About 1100' east of the eastern end of the cut.	Matrix of Y-51.	Clast in ouachitite; ~3 cm white- yellowish clast with reddish spots, gneiss-like.
Y-50	Y-51	Y-52	Y-56

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The minette sill is composed of pyroxene (5%) , < 1 mm and phlogopite $(2 \text{ to } 3\%)$, < 3 mm in a matrix of K-feldspars (60%) 0.3 mm in length, micas $(15\%, 0.3 \text{ mm})$, opaques (3%) and quartz. Green-yellow alteration covers about 15% of the section and outlines all of the minerals. About 2 to 3% of the total pyroxene and phlogopites are phenocrysts. Micas are purple-orange-brown with normal pleochroism. They are probably biotitic in composition. Some crystals have a light coloured core which is probably phlogopite. The pyroxenes still have some fresh areas. The other section (with xenolith) is slightly more altered.
Strongly weathered minette sill. Fungus were growing in the pail after only two weeks of storage.
Y-57 (2)

selected due to the presence of these features. Occasionally, two numbers are given in the column for ocelli; the first refers to the amount of ocelli, the second to the percentage. When only one number is given, it refers to the percentage of ocelli in the section. Sections Y-44b, Y-(phlogopite), OT (other), OX (oxides). Ocelli and xenoliths were not included in the total of the mode because many of the sections were Table D.2: Mode of the minerals present in the Yogo dike, in percent. The symbols used in the table are DI (diopside), GRN (groundmass), PH 46, Y-47, Y-48b, Y-49, Y-50, Y-56, and Y-57 are too weathered to recognize the primary minerals.

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Remarks			30% secondary biotite.				Others include a serpentine megacryst and a large cracked pyroxene.	Not a good section.		Vein in the section.	Highly weathered section.		Oxides $< 0.1 \text{ mm}$.		1 sapphire.			Pyroxenite xenolith.	Pyroxenite xenolith. Ocelli are 1 to 2 mm.
XO		2	2	3	3	2	5	2	я	2			3	2 .	2		2		2
OT							2												
Ocelli	(number, %)	< 1	2		10	15		30		1, < 1			1,1	i	1		i	?	1
GRN		65	65	60	57	55	55	60	60	55			50	55	50		50		55
trix	DI	10	15	15	20	20	25	20	20	20			25	25	26		25		25
Mat	Hd	15	0	ί	15	15	10	10	10	15			15	10	15		15		10
ıcryst	DI	2	15	7	3	5	S	7	5	7			5	5	3		5		7
Mega	Hd	5	3	15	7	2	1	1	1	-	15	1	-	1	3		7		-
Sample		Y-11a (1)	Y-11a (2)	Y-11b	Y-12a	Y-12b	Y-12c	Y-12d	Y-12e	Y-13	Y-16	Y-18b	Y-21	Y-23a	Y-23b	Y-24	Y-25a	Y-25b	Y-25c

		Xenolith with a lot of spinels.		Ocelli < 3 mm.	Xenolith with a lot of spinels.	Others include a serpentine xenolith.	Spinel xenolith.		Spinel xenolith.		1 sapphire.	Others include a xenolith with chrome-spinel.					1 sapphire.	Others include a serpentine megacryst.	See section Y-13.				
5	2	2	2	2	1	2	2	1	1	1	-	1	1	2	1	2	3	3	1	2	2	1	1
						2						3						2					
5	0	1 to 2	0	ю	ć	0	ί	0	10	2		1	0	1	2	15	٤	3	ė	5	5	0	0
50	55	55	55	55	55	50	50	50	50	50	50	50	45	55	50	55	48	55	55	50	50	50 -	52
25	20	20	25	20	25	20	20	30	25	23	20	25	25	30	20	20	35	25	15	20	20	20	25
15	15	12	12	15	10	16	20	10	20	15	20	15	20	7	20	15	7	7	20	17	15	20	15
5	5	7	s	S	5	5	5	5	e	10	S	5	7	5	S	5	5	5	S	7	7	7	5
	-	5	1	7	2	m	2	2	-	2	2		2	1	2	2	1	1	3	3	3	1	2
Y-25d	Y-25e	Y-25f	Y-31a	Y-31b	Y-31c	Y-31d	Y-31e	Y-31f	Y-31g	Y-31h	Y-31i	Y-31j	Y-31k	Y-311	Y-31m	Y-32	Y-33a	Y-33b	Y-34	Y-35a	Y-35b	Y-42a	Y-42b

Table D.2: (Mode of the minerals present in the Yogo dike) continued.

	j.				
Ocelli < 1 mm.	15% of voids. "Total includes phenocrysts." 5% uncertain	°5% relics.	Ocelli up to 6 mm.	Fuschite?	
1	1	-	1	2	
1	0	0	5		
50		60 to 65	55	75	
25	10 ^b	10°	20	5	
15	20ª	20	15	15	35
5			5		
2			2		
Y-42c	Y-43a	Y-43b	Y-44a	Y-48a	Y-51

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Table D.2: (Mode of the minerals present in the Yogo dike) continued.

APPENDIX E

ELECTRON MICROPROBE ANALYSES

Table E.1:	Chemical c	omposition o	f Yogo pyro:	xenes. Diagi	rams of the g	trains analyz	ed are shown	n at the end o	of Appendix	E.1.	
	33A2-1	33A2-2	33A2-3	33A2-4	33A2-5	33A3-2	33A3-3	33A3-4	33A3-5	33A3-6	33A3-7
	Rim	Rim	Core	Core	Core	Rim2	Core	Core	Core	Rim2	Rim2
SiO	43.73	42.84	51.08	51.05	50.67	51.71	54.61	54.70	54.84	52.43	51.97
A, Ó	9.70	10.20	4.38	4.17	4.75	3.17	0.43	0.34	0.39	2.79	2.79
FeÓ	0.54	0.60	2.18	1.74	1.59	1.19	0.00	0.00	00.00	0.88	0.46
Fe_O_	6.29	7.56	2.57	3.02	3.17	2.32	0.87	0.79	0.73	2.53	3.09
Tiố	2.05	1.91	0.50	0.49	0.41	0.30	0.02	0.03	00.0	0.25	0.24
Cr_0	0.16	0.03	0.44	0.32	0.45	1.64	0.03	0.00	0.00	1.50	0.95
Mno	0.05	0.05	0.11	0.13	0.12	0.09	0.07	0.09	0.12	0.08	0.09
NiO	0.03	0.01	0.02	0.02	0.06	0.03	0.03	0.01	00.0	0.05	0.04
Mg0	12.10	11.31	16.06	16.32	15.94	17.01	18.16	18.38	18.07	17.40	17.35
CaO	24.03	23.88	21.02	20.91	20.91	20.85	25.33	25.34	25.33	21.22	21.36
NaO	0.25	0.33	0.79	0.80	0.86	0.82	0.26	0.21	0.26	0.80	0.75
TÓTAL	98.93	98.71	99.14	98.95	98.91	99.13	99.79	99.89	99.73	99.92	99.10
Si	1.65	1.62	1.88	1.88	1.87	1.90	1.98	1.98	1.99	1.91	1.90
AlIV	0.36	0.38	0.12	0.12	0.13	0.10	0.02	0.02	0.01	0.10	0.10
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
AI	0.08	0.08	0.07	0.06	0.07	0.03	00.0	0.00	0.00	0.03	0.02
Fe	0.18	0.22	0.07	0.08	0.09	0.06	0.02	0.02	0.02	0.07	0.09
Ti 4	0.06	0.05	0.01	0.01	0.01	0.01	0.00	0.00	00.00	0.01	0.01
Cr [*]	0.01	0.00	0.01	0.01	0.01	0.05	0.00	0.00	00.00	0.04	0.03
Mg ²⁺	0.68	0.64	0.83	0.84	0.82	0.85	0.97	0.98	0.98	0.85	0.86
Fe ^{z‡}	0.00	0.01	0.00	00.00	0.00	0.00	0.00	00.0	0.00	00.0	0.00
Sum	1.00	1.00	1.00	1.01	1.01	1.00	1.00	1.00	1.00	1.00	1.00
${ m Mg}^{2+}$	00.0	00.0	0.05	0.06	0.06	0.08	0.01	0.01	0.00	0.09	0.0
Fe 4	0.02	0.01	0.07	0.05	0.05	0.04	0.00	0.00	00.00	0.03	0.01
Mu ²⁺	0.00	00.0	0.00	00.0	0.00	0.00	0.00	0.00	00.0	00.0	00.00
Ca t	0.97	0.97	0.83	0.82	0.83	0.82	0.98	0.98	0.98	0.83	0.84
Na^+	0.02	0.02	0.06	0.06	0.06	0.06	0.02	0.02	0.02	0.06	0.05
Sum	1.01	1.01	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.00	1.00

Table E.1: (Chemic	cal compositi	on of Yogo	pyroxenes) c	ontinued.							
	33A2-1	33A2-2	33A2-3	33A2-4	33A2-5	33A3-2	33A3-3	33A3-4	33A3-5	33A3-6	33A3-7
	Rim	Rim	Core	Core	Core	Rim2	Core	Core	Core	Rim2	Rim2
č	57 10	57 55	9L VV	21 VV	<i>V</i> VV	71 IV	00 0V	<i>10 77</i>	40 57	06 44	44 37
Ca	74.42	CC.7C		11.17	F0.FF	11.17		17.71		14.11	
Mg	36.77	34.60	47.57	48.21	47.62	50.16	49.25	49.57	49.22	50.40	50.24
$\operatorname{Fe}_{\mathrm{T}}(1)$	10.74	12.85	7.68	7.66	7.74	5.66	1.36	1.20	1.21	5.31	5.45
mg	77.57	73.08	86.36	86.62	86.36	90.12	97.51	97.92	97.99	90.65	90.48
)											
Mg/(Mg+Fe2+)	0.98	0.98	0.93	0.94	0.94	0.96	1.00	1.00	1.00	0.97	0.98
Mg/(Mg+Fer)	0.78	0.74	0.86	0.86	0.86	0.89	0.98	0.98	0.98	0.90	06.0
100Fe2+	2.45	1.54	7.47	6.04	5.64	4.17	0.00	0.00	0.00	3.08	1.60
/(Fe2++Mg)											
100Ca/(Ca+Mg)	58.81	60.30	49.94	49.52	50.15	49.07	50.33	50.08	50.18	49.28	49.35
Name	subsilicic a	luminian	Magnesian	calcian alun	ninian chrom	ian augite	diopside	diopside	diopside	Magnesiar	calcian
	ferrian d	iopside)			I	I	I		aluminian	chromian
										augi	te
End-members:											
NaFe [*] Si ₂ O ₂	0.018	0.024	0.056	0.057	0.061	0.058	0.018	0.015	0.018	0.056	0.053
NaAlSi_O	0.000	0.000	0.000	0.000	0.000	0.000	000.0	0.000	0.000	0.000	0.000
CaTiAIÂIÔ	0.058	0.054	0.014	0.014	0.011	0.008	0.001	0.001	0.000	0.007	0.007
CaFe ^{*+} AlSiÔ ₂	0.160	0.191	0.015	0.027	0.027	0.006	0.006	0.006	0.002	0.013	0.032
CaCrAISiO	0.005	0.001	0.013	0.009	0.013	0.048	0.001	0.000	0.000	0.043	0.028
CaAIAISiO	0.075	0.078	0.067	0.059	0.072	0.034	0.005	0.004	0.007	0.025	0.023
Ca_Si_O_ (Ŵo)	0.335	0.323	0.360	0.358	0.351	0.362	0.485	0.486	0.487	0.369	0.374
Mg Si O (En)	0.339	0.319	0.440	0.450	0.440	0.465	0.490	0.495	0.488	0.470	0.475
Fe _. Śi,Ó, (Fs)	0.009	0.010	0.034	0.028	0.026	0.019	0.001	0.000	0.000	0.014	0.008
Total	0.999	0.999	0.999	1.001	1.001	0.999	1.006	1.007	1.002	0.997	1.000
(1) $\operatorname{Fe}_{\mathrm{T}} = \operatorname{Fe}^{3++} \operatorname{Fe}^{3+-}$	++ Mn2+										

Table E.1:	(Chemical c	omposition of 33 A4-7	f Yogo pyro 33 A4-3	xenes) contin 33 A4-4	13.44-5	G5-1	G5-2	G5-3	G5-4	G5-5	G5-6
	Riml	Core	Core	Core	Rim1	Rim	Core	Core	Core	Core	Rim
SiO	42.85	51.55	51.92	50.38	43.29	49.24	50.84	52.39	49.55	50.82	50.93
A,Ô	10.53	2.99	2.39	5.56	10.17	3.38	2.23	2.35	2.31	2.61	2.49
FeO	1.36	0.59	0.55	0.88	0.85	00.0	0.00	1.35	0.00	0.24	0.04
FeO	5.90	2.94	3.07	3.47	7.30	3.50	3.46	2.04	3.63	3.35	3.43
Tiố	2.57	0.28	0.23	0.44	1.62	0.31	0.22	0.27	0.29	0.29	0.30
ĊŗŎ	0.12	1.47	1.64	0.28	00.0	0.72	0.89	0.49	0.51	0.58	1.03
MnO	0.06	0.07	0.10	0.08	0.07	0.12	0.10	0.06	0.08	0.05	0.10
NiO	00.0	0.02	0.03	0.01	00.0	0.07	0.05	0.07	0.02	0.06	0.03
MgO	11.47	17.21	17.69	16.19	11.43	15.72	17.35	17.45	17.59	17.19	17.05
CaO	23.75	20.90	20.40	20.90	23.65	21.49	21.69	21.41	21.22	21.06	21.21
Na ₀	0.27	0.81	0.85	0.87	0.35	1.04	0.69	0.62	09.0	0.66	0.74
TÓTAL	98.88	98.84	98.86	99.07	98.74	95.59	97.52	98.50	95.80	96.91	97.35
Si	1.62	1.89	1.91	1.85	1.64	1.88	1.90	1.93	1.88	1.90	1.90
AIV	0.38	0.11	0.09	0.15	0.36	0.12	0.10	0.07	0.10	0.10	0.10
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	1.98	2.00	2.00
M	0.09	0.02	0.01	0.09	0.09	0.03	0.00	0.03	0.00	0.02	0.01
Fe^{3+}	0.17	0.08	0.09	0.10	0.21	0.10	0.10	0.06	0.08	0.09	0.10
∐; €	0.07	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01
C,	00.0	0.04	0.05	0.01	00.00	0.02	0.03	0.01	0.02	0.02	0.03
$M_{g}^{2^{+}}$	0.65	0.84	0.85	0.80	0.64	0.84	0.86	0.89	0.89	0.86	0.85
Fe	0.02	00.0	0.00	0.00	0.01	0.00	00.0	00.0	0.00	00.00	00.00
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
${ m Mg}^{2+}$	00:0	0.10	0.12	0.09	0.00	0.05	0.11	0.07	0.11	0.10	0.10
Fe 4	0.02	0.02	0.02	0.03	0.02	00.0	0.00	0.04	0.00	0.01	00.0
${ m Mn}^{2+}$	00.0	0.00	0.00	0.00	0.00	00.0	0.00	0.00	00.00	0.00	00.0
Ca	0.96	0.82	0.80	0.82	0.96	0.88	0.87	0.84	0.86	0.84	0.85
Na^{+}	0.02	0.06	0.06	0.06	0.03	0.08	0.05	0.04	0.04	0.05	0.05
Sum	1.00	1.00	1.00	1.00	1.01	1.01	1.03	0.99	1.01	1.00	1.00

Table E.1: (Chem	ical composit	ion of Yogo p	ivroxenes) c	continued.						i	
	33A4-1	33A4-2	33A4-3	33A4-4	33A4-5	G5-1	G5-2	G5-3	G5-4	G5-5	G5-6
	Riml	Core	Core	Core	Riml	Rim	Core	Core	Core	Core	Rim
, L	67 00	AA 12	12 67	CL VV	52 01	47 DK	44.85	10 00	44 33	10 71	44 74
Ca	60.70	14+. IJ	1/.71	11.12	10.70						
Mg	35.54	50.40	51.65	48.47	34.96	47.59	00.00	50.05	دد.۱د	£C.0C	00.00
Fe _T (1)	11.57	5.47	5.64	6.81	13.03	5.35	5.15	5.26	4.12	5.26	5.26
Bm	75.62	90.38	90.40	87.86	73.02	89.90	90.65	90.57	92.59	90.57	90.48
Mg/(Mg+Fe2+)	0.97	0.98	0.98	0.97	0.97	1.00	1.00	0.96	1.00	0.99	1.00
Mg/(Mg+Fer)	0.77	0.89	0.89	0.87	0.74	0.89	06.0	06.0	0.92	06.0	0.89
100Fe2+	3.01	2.10	1.96	3.26	3.01	0.00	0.00	4.30	0.00	1.15	0.00
/(Fe2++Mg)								10 55	11.01	11 01	0002
100Ca/(Ca+Mg)	59.81	49.49	48.55	C0.UC	08.60	01.10	67.UC	48.00	49.14	49.41	
Name	subsilicic	Magnesiar	n calcian	Magnes-	subsilicic	Aluminia	magne-		the reduction of	ncinian	magne-
	aluminian ferrian	aluminian (augi	chromian te	1an calcian	aluminian ferrian	n rernan chromian	sian calcian	chr	omian augite		calcian
	diopside)		aluminian	diopside	diopside	aluminian				aluminian
				chromian			chromian				ferrian
				fernan			ternan				chromian
End-members:				augus			angun a				
NaFe [*] Si ₂ O ₂	0.020	0.058	0.061	0.062	0.026	0.080	0.050	0.040	0.040	0.050	0.050
NaAlSi Ó	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	000.0
CaTiAlÅlÖ	0.073	0.008	0.006	0.012	0.046	0.010	0.010	0.010	0.010	0.010	0.010
CaFe ³⁺ AlSiÔ	0.148	0.023	0.024	0.034	0.182	0.020	0.050	0.020	0.040	0.040	0.050
CaCrAISiO	0.004	0.043	0.048	0.008	0.000	0.020	0.030	0.010	0.020	0.020	0.030
CaAIAISiO	0.085	0.024	0.010	0.087	060.0	0.045	0.000	0.025	0.010	0.020	0.005
Ca_Si_O_(Ŵo)	0.325	0.363	0.357	0.340	0.320	0.393	0.390	0.388	0.390	0.375	0.378
Mg Si O (En)	0.323	0.470	0.485	0.445	0.322	0.445	0.485	0.480	0.500	0.480	0.475
Fe Ši Ó (Fs)	0.020	0.010	0.009	0.014	0.015	0.000	0.000	0.020	0.000	0.005	0.000
Total	0.998	0.998	1.000	1.002	1.001	1.013	1.015	0.993	1.010	1.000	0.998
(1) $Fe_{T} = Fe^{3++} F$	e2++ Mn2+										

ble E.1	<u>G2-1</u>	composition G2-1	of Yogo py G2-2	roxenes) cont G2-3	inued. G2-4	G2-5	G2-6	G2-7	G3-1	G3-2
		Smai	Il Pyroxene	grains in and	outside Phlo	gopite pheno	ocryst		Patchy	pyroxene
	53.71	52.14	52.41	52.69	51.80	48.77	51.34	51.27	50.26	47.15
، ص	3.22	3.10	3.39	2.95	3.37	5.16	4.11	4.46	6.12	5.63
^	3.31	1.57	1.88	2.20	1.71	0.33	1.08	1.51	1.68	0.00
ဝ်	00.00	2.05	1.81	1.80	3.01	4.52	2.54	2.51	2.70	4.63
` _`	0.27	0.27	0.29	0.33	0.29	0.39	0.34	0.40	0.41	0.42
ؘٛڡ	0.45	0.53	0.51	0.13	0.42	0.38	0.53	0.62	0.01	0.06
°	0.09	0.08	0.13	0.14	0.14	0.08	0.09	0.09	0.12	0.12
~	0.06	00.0	0.05	00.00	00.00	00.00	0.07	0.03	0.04	0.02
0	16.64	17.00	16.87	17.27	17.44	17.01	16.30	15.95	14.94	15.43
~	21.46	21.41	21.36	21.49	20.27	20.10	21.69	22.06	21.64	21.30
0	00.0	0.69	0.74	0.57	0.71	0.47	0.78	0.72	0.92	0.80
FAL	99.21	98.84	99.44	99.57	99.16	97.21	98.87	99.62	98.84	95.56
	1.96	1.91	1.91	1.92	1.90	1.82	1.89	1.87	1.85	1.80
~	0.04	0.09	0.09	0.08	0.10	0.18	0.11	0.13	0.15	0.20
-	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	0.10	0.04	0.06	0.05	0.05	0.05	0.07	0.06	0.12	0.05
	00.0	0.06	0.05	0.05	0.08	0.13	0.07	0.07	0.07	0.13
	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4	0.01	0.02	0.01	00.0	0.01	0.01	0.02	0.02	0.00	0.00
F	0.88	0.87	0.87	0.89	0.85	0.80	0.83	0.84	0.80	0.81
	00'0	00.0	0.00	00.0	00.0	00.0	0.00	0.00	0.00	0.00
_	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
+	0.02	0.06	0.05	0.05	0.10	0.15	0.06	0.03	0.02	0.07
-	0.10	0.05	0.06	0.07	0.05	0.01	0.03	0.05	0.05	00.0
+	00.0	00.00	0.00	00.0	00.00	00.0	0.00	0.00	0.00	0.00
	0.84	0.84	0.84	0.84	0.80	0.81	0.85	0.86	0.85	0.87
	00.0	0.05	0.05	0.04	0.05	0.03	0.06	0.05	0.07	0.06
ľ	0.96	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00

Table E. 1: (Chemi	ical composit	tion of Yogo	pyroxenes)	continued.						
	G2-1	G2-1	G2-2	G2-3	G2-4	G2-5	G2-6	G2-7	G3-1	G3-2
		Small	Pyroxene g	rains in and	outside Phlc	gopite pheno	ocryst		Patchy pyre	oxene
Ca	45.65	44.68	44.92	44.21	42.55	42.63	46.20	46.49	47.49	46.28
Mg	48.91	49.47	49.20	49.47	50.53	50.00	48.37	47.03	45.81	46.81
Fe _x (1)	5.43	5.85	5.88	6.32	6.91	7.37	5.43	6.49	6.70	6.91
1 × 1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
шg	00.06	89.42	89.32	88.68	87.96	87.16	89.90	87.88	87.23	87.13
Mg/(Mg+Fe2+)	06.0	0.95	0.94	0.93	0.94	0.99	0.97	0.94	0.94	1.00
Mg/(Mg+Fer)	0.90	0.89	0.89	0.88	0.87	0.85	0.89	0.88	0.87	0.86
100Fe2+	10.20	5.43	6.45	7.29	5.56	1.23	3.49	5.62	5.88	0.00
/(Fe2++Mg)										
100Ca/(Ca+Mg)	48.84	49.12	49.12	48.55	48.48	50.31	50.60	50.59	51.52	51.79
Name	aluminian	Magnesian	calcian alui	ninian chron	nan augite	magne.	Aluminia	n chromian	Alumini	ın ferrian
	chromian)				calcian	diol	pside	diop	side
	ferroan					aluminian				
	diopside					ternan chromian				
						augite				
End-members: NaFe_Si O	000.0	0.050	0.050	0.040	0.050	0.030	0.060	0.050	0.070	0900
NaAlSi 0	0.000	0.000	0.000	0.000	0.000	000.0	0.000	0.000	0.000	0.000
CaTiAlÅlÔ	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
CaFe ³⁺ AlSiÔ	0.000	0.010	0.000	0.010	0.030	0.100	0.010	0.020	0000	0.070
CaCrAISiO	0.010	0.020	0.010	0.000	0.010	0.010	0.020	0.020	0.000	0.000
CaAIAISiO	0.055	0.040	0.060	0.050	0.045	0.050	0.065	0.065	0.125	0.080
Ca _s Si O (Ŵo)	0.383	0.380	0.380	0.385	0.353	0.320	0.373	0.373	0.358	0.355
Mg Si O (En)	0.450	0.465	0.460	0.470	0.475	0.475	0.445	0.435	0.410	0.440
Fe _, Ši,Ô, (Fs)	0.050	0.025	0.030	0.035	0.025	0.005	0.015	0.025	0.025	0.000
Total	0.958	1.000	1.000	1.000	0.998	1.000	0.998	0.998	0.998	1.015
(1) $Fe_{T} = Fe^{3++} F_{0}$	2++ Mn2+									

Table E.1: ((Chemical co	imposition of	f Yogo pyro>	xenes) contin	ued.					
	G3-3	G3-4	G4-1	G4-2	G4-3	G4-4	G4-5	G4-6	G4-7	G4-8
	Patchy p	yroxene	Rim	Core	Core	Rim 2	Rim	Rim	Core	Core
SiO	50.95	47.35	43.89	52.27	52.81	51.77	45.68	46.34	52.55	52.91
АŢÓ	4.17	7.86	8.44	2.50	2.34	3.15	8.22	6.44	2.32	1.76
FeÓ	1.01	1.13	0.68	0.55	1.43	0.58	0.00	0.40	2.28	1.90
Fe,O	3.05	4.17	7.01	2.40	1.50	2.87	5.46	5.64	1.28	1.95
Tiố	0.29	0.82	1.93	0.23	0.24	0.26	1.36	1.59	0.29	0.23
ĊŗŎ	0.08	0.08	0.03	1.21	0.78	0.65	0.22	0.33	1.17	0.71
MnO	0.10	0.06	0.07	0.07	0.09	0.14	0.07	0.04	0.07	0.10
NiO	0.03	0.01	00.0	0.07	0.14	0.04	0.02	0.00	0.05	0.06
MgO	16.22	13.25	12.29	17.78	17.37	17.00	13.41	13.78	17.40	18.22
CaO	21.62	22.90	23.73	21.32	21.68	21.90	23.51	23.98	20.63	20.41
Na ₀ O	0.74	0.69	0.25	0.65	0.64	0.65	0.41	0.24	0.70	09.0
TOTAL	98.26	98.32	98.32	99.05	99.02	99.01	98.36	98.78	98.74	98.85
Si	1.88	1.77	1.67	1.91	1.93	1.90	1.71	1.74	1.93	1.94
AIIV	0.12	0.23	0.33	0.09	0.07	0.10	0.29	0.26	0.07	0.06
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
AL	0.06	0.12	0.05	0.02	0.03	0.04	0.07	0.02	0.03	0.02
Fe	0.08	0.12	0.20	0.07	0.04	0.08	0.15	0.16	0.04	0.05
Ti ⁴	0.01	0.02	0.06	0.01	0.01	0.01	0.04	0.04	0.01	0.01
Cr [*]	0.00	0.00	00.0	0.03	0.02	0.02	0.01	0.01	0.03	0.02
$M_{B}^{2^{+}}$	0.85	0.74	0.69	0.87	06.0	0.85	0.73	0.77	0.89	0.90
Fe 74	00.0	00.0	00.0	00.0	0.00	00.0	0.00	00.00	00.00	0.00
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mg^{2+}	0.04	00.00	0.01	0.10	0.05	0.08	0.02	00.0	0.06	0.10
Fe 4	0.03	0.04	0.02	0.02	0.04	0.02	0.00	0.01	0.07	0.06
Mn ²⁺	0.00	0.00	00.00	0.00	0.00	00.0	00.0	0.00	0.00	0.00
Ca	0.86	0.92	0.96	0.84	0.85	0.86	0.94	0.96	0.81	0.80
Na^{+}	0.05	0.05	0.02	0.05	0.05	0.05	0.03	0.02	0.05	0.04
Sum	0.98	1.01	1.01	1.01	0.99	1.01	0.99	0.99	0.99	1.00

Table E. I: (Chemi	cal compositi	ion of Yogo p	oyroxenes) c	ontinued.						
	G3-3	G3-4	G4-1	G4-2	G4-3	G4-4	G4-5	G4-6	G4-7	G4-8
	Patchy p	yroxene	Rim	Core	Core	Rim 2	Rim	Rim	Core	Core
Ca	46.24	50.55	51.06	44.21	45.21	45.50	51.09	50.53	43.32	41.88
Mg	47.85	40.66	37.23	51.05	50.53	49.21	40.76	40.53	50.80	52.36
Fe _T (1)	5.91	8.79	11.70	4.74	4.26	5.29	8.15	8.95	5.88	5.76
Bm	89.00	82.22	76.09	91.51	92.23	90.29	83.33	81.91	89.62	90.09
Mg/(Mg+Fe2+)	0.97	0.95	0.97	0.98	96.0	0.98	1.00	0.99	0.93	0.94
Mg/(Mg+Fer)	0.89	0.82	0.76	0.91	0.92	0.89	0.83	0.82	0.89	0.89
100Fe ²⁺	3.41	5.13	2.82	2.25	4.26	2.30	0.00	1.28	7.29	6.25
/(Fe2++Mg)										
100Ca/(Ca+Mg)	50.29	55.42	58.18	49.12	48.57	50.29	56.29	55.49	47.65	47.06
Name	Aluminian	Aluminia	subsilicic	magne-	Aluminian	chromian	subsilicic	subsilicic	magnesian	calcian
	diopside	n ferrian	aluminian	sian	diops	side	aluminian	aluminian	chromian	augite
		diopside	ferrian	calcian			fernan	fernan		
			diopside	aluminian			chromian	chromian		
				chromian augite			aiopsiae	aiopsiae		
End-members:				Andarn						
NaFe ³⁺ Si O	0.050	0.050	0.020	0.050	0.040	0.050	0.030	0.020	0.040	0.040
NaAISi,Ó	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.010	0.000
CaTiAIAIÔ	0.010	0.020	0.060	0.010	0.010	0.010	0.040	0.040	0.010	0.010
CaFe ^{*+} AlSiÔ ₂	0.030	0.070	0.180	0.020	0.000	0.030	0.120	0.140	0.000	0.010
CaCrAISiO [°]	0.000	0.000	0.000	0.030	0.020	0.020	0.010	0.010	0.030	0.020
CaAIAISiO	0.065	0.120	0.040	0.020	0.025	0.035	0.075	0.025	0.020	0.015
Ca Si O (Wo)	0.378	0.355	0.340	0.380	0.398	0.383	0.348	0.373	0.375	0.373
Mg Si O (En)	0.445	0.370	0.350	0.485	0.475	0.465	0.375	0.385	0.475	0.500
Fe Ši Ó (Fs)	0.015	0.020	0.010	0.010	0.020	0.010	0.000	0.005	0.035	0.030
Total ^{°°}	0.993	1.005	1.000	1.005	866.0	1.003	0.998	0.998	0.995	0.998
$(1) \operatorname{Fe}_{\mathrm{T}} = \operatorname{Fe}^{3++} \operatorname{Fe}$	2++ Mn2+									

Table E.1:	(Chemical co	imposition of	f Yogo pyro>	kenes) contin	ued.					
	G6-1	G6-2	G6-3	G6-4	G6-5	G6-6	G8-1	G8-2	G8-3	G8-4
	Rim	Core	Core	Core	Core	Rim	Rim 2	Rim 1	Core	Rim 1
SiO	49.15	52.45	51.21	52.86	52.53	44.10	40.96	48.56	51.21	46.61
Al,Ô,	7.06	2.29	2.29	2.15	1.84	7.09	10.18	8.24	4.86	7.17
FeÓ	0.67	3.14	1.22	2.81	1.65	00.00	0.00	1.35	2.05	0.00
FeO	3.54	1.96	4.37	2.71	1.54	6.79	8.70	3.34	2.91	4.69
TiÔ,	0.46	0.13	60.0	0.11	0.24	1.72	2.40	0.62	0.19	0.75
ĊŗÓ	0.14	0.06	0.00	00.0	1.07	0.06	0.00	0.10	0.24	0.08
MnŐ	0.10	0.41	0.56	0.42	0.09	0.07	0.09	0.12	0.10	0.07
NiO	0.09	0.00	0.00	00.0	0.02	00.00	0.02	0.05	0.02	0.00
MgO	15.46	15.89	15.88	15.95	17.64	12.75	11.32	14.25	15.06	14.46
CaO	21.01	20.94	20.97	21.22	20.82	23.86	23.88	21.63	20.32	22.88
Na ₀ O	0.83	0.89	0.94	0.96	0.68	0.27	0.25	0.86	1.37	0.57
TÓTAL	98.51	98.16	97.53	99.19	98.12	96.71	97.80	99.12	98.33	97.28
Si	1.81	1.95	1.92	1.95	1.94	1.70	1.57	1.79	1.89	1.76
AIIV	0.19	0.05	0.08	0.05	0.06	0.30	0.43	0.21	0.11	0.24
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
A	0.12	0.05	0.02	0.04	0.02	0.02	0.03	0.15	0.10	0.08
Fe.	0.10	0.05	0.12	0.08	0.04	0.20	0.25	0.09	0.08	0.13
Ti [‡]	0.01	0.00	00.0	00.0	0.01	0.05	0.07	0.02	0.01	0.02
Cr [‡]	00.0	00.0	00.0	00.0	0.03	0.00	0.00	00.00	0.01	0.00
Mg.	0.77	0.88	0.86	0.88	06.0	0.73	0.65	0.74	0.80	0.77
Fe	00.0	0.02	00.00	00.00	00.0	00.0	00.00	00.0	0.00	0.00
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$M_{E}^{2^{+}}$	0.08	00.0	0.03	00.0	0.07	00.0	00.0	0.04	0.03	0.04
Fe	0.02	0.08	0.04	0.09	0.05	0.00	0.00	0.04	0.06	0.00
Mn_{1}^{2+}	00.0	0.01	0.02	0.01	0.00	0.00	0.00	0.00	00.0	00.00
Ca_{t}	0.83	0.83	0.84	0.84	0.82	0.98	0.98	0.85	0.81	0.92
Na	0.06	0.06	0.07	0.07	0.05	0.02	0.02	0.06	0.10	0.04
Sum	0.99	0.98	1.00	1.01	0.99	1.00	1.00	0.99	1.00	1.00

Table E.1: (Chemi	cal compositi	ion of Yogo p	oyroxenes) co	ntinued.						
	G6-1	G6-2	G6-3	G6-4	G6-5	G6-6	G8-1	G8-2	G8-3	G8-4
	Rim	Core	Core	Core	Core	Rim	Rim 2	Rim 1	Core	Rim 1
Č	46 11	44 39	43 98	44.21	43 62	51.31	52.13	48.30	45.51	49,46
Ma	47.77	47.06	46.60	46.32	51.60	38.77	34 57	44 37	46.63	43 55
Fe (1)	6.67	8.56	9.42	9.47	4.79	10.47	13.30	7.39	7.87	6.99
	5		1	-						
тв	87.63	85.44	84.76	83.81	91.51	78.49	72.22	85.71	85.57	86.17
Mg/(Mg+Fe2+)	0.97	0.92	0.96	0.91	0.95	1.00	1.00	0.95	0.93	1.00
Mg/(Mg+Fer)	0.87	0.87	0.84	0.84	0.91	0.78	0.72	0.85	0.85	0.86
100Fe2+ /(Fe2++Μσ)	2.53	8.33	4.44	9.28	5.26	0.00	0.00	5.13	6.98	0.00
100Ca/(Ca+Mg)	51.88	48.54	49.41	48.84	47.67	57.31	60.12	53.46	50.31	54.44
Name	Aluminian	magne-	magne-	magne-	magne-	Subsilicic a	luminian	subsilicic	aluminian	subsilicic
	diopside	sian	sian	sian	sian	ferrian di	iopside	aluminian	chromian	aluminian
		calcian	calcian	calcian	calcian			diopside	diopside	ferrian
		aluminian	aluminian	augite	chromian					diopside
		ferroan	ferrian		augite					
		augite	augite							
End-members:	0.060	0.050	0200	0.070	0100	0.000	0.000	0.060	0.080	0.040
NaAISi O	0.000	0.010	0.000	0.000	0.010	0.000	0.000	0.000	0.020	0.000
CaTiAlÅlÔ	0.010	0.000	0.000	0.000	0.010	0.050	0.070	0.020	0.010	0.020
CaFe ^{*+} AlSiÔ ₂	0.040	0.000	0.050	0.010	0.000	0.180	0.230	0.030	0.000	060.0
CaCrAISiO ₆	0.000	0.000	000.0	0.000	0.030	0.000	0.000	0.000	0.010	0.000
CaAIAISiO	0.125	0.045	0.025	0.040	0.010	0.020	0.045	0.145	0.080	0.095
Ca,Si,O, (Wo)	0.328	0.393	0.383	0.395	0.385	0.365	0.318	0.328	0.355	0.358
Mg Si O (En)	0.425	0.440	0.445	0.440	0.485	0.365	0.325	0.390	0.415	0.405
Fe,Ši,Õ, (Fs)	0.010	0.050	0.020	0.045	0.025	0.000	0.000	0.020	0.030	0000
Total	0.998	0.988	0.993	1.000	0.995	1.000	1.008	0.993	1.000	1.008
(1) $Fe_{r} = Fe^{3++} Fe$	2++ Mn2+									

Table E.1:	(Chemical c	composition c	of Yogo pyro	xenes) conti	nued.						
	G7-1	G7-2	G7-3	G7-4	G7-5	G7-6	G7-7	G7-8	G7-9	G7-10	G7-11
	Rim 3	Rim 2	Core	Core	Rim 4	Rim 3	Rim 2	Rim 2	Rim 1	Rim 1	Core
SiO	49.14	48.25	48.15	47.97	40.39	46.69	47.18	47.56	48.66	48.73	49.05
AI,Ô,	7.42	90.6	69.9	6.56	10.30	8.53	8.44	9.19	4.89	4.61	6.72
FeÓ	1.10	1.41	5.89	5.25	0.00	0.11	0.00	0.66	4.87	5.46	6.32
Fe,O,	3.43	3.12	4.29	4.93	10.28	5.18	4.67	3.94	5.07	3.98	3.63
TiÔ	0.51	0.53	0.74	0.74	2.04	0.94	0.58	0.61	0.65	0.70	0.68
Ċŗ,Ŏ	0.10	0.17	0.04	0.01	00.0	0.13	0.16	0.26	0.02	0.03	0.00
MnO	0.13	0.08	0.04	0.06	0.13	0.07	0.07	0.05	0.08	0.05	0.10
NiO	0.01	0.04	0.05	0.05	0.09	0.03	00.00	0.03	0.05	0.05	0.04
Mg0	14.45	13.48	10.59	10.63	10.08	13.30	13.80	13.35	12.19	12.35	10.69
CaO	21.60	21.58	19.00	19.15	23.70	22.96	21.54	21.47	20.81	21.23	19.28
Na,O	0.98	1.07	1.95	1.98	0.35	0.72	1.07	1.16	1.16	0.89	1.95
TÓTAL	98.87	98.79	97.43	97.33	97.36	98.66	97.51	98.28	98.45	98.08	98.46
Si	1.81	1.78	1.84	1.83	1.57	1.74	1.77	1.76	1.84	1.85	1.85
AlIV	0.19	0.22	0.16	0.17	0.43	0.26	0.23	0.24	0.16	0.15	0.15
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Al	0.13	0.17	0.14	0.13	0.04	0.11	0.14	0.16	0.06	0.06	0.15
Fe.	0.10	0.09	0.12	0.14	0.30	0.15	0.13	0.11	0.14	0.11	0.10
Ti _+	0.01	0.01	0.02	0.02	0.06	0.03	0.02	0.02	0.02	0.02	0.02
ں ت	00 [.] 00	00.0	00.0	0.00	00.0	0.00	0.00	0.01	0.00	0.00	0.00
No.4	0.76	0.73	09.0	0.61	0.58	0.71	0.77	0.70	0.69	0.70	09.0
Fe	00.00	0.00	0.12	0.10	00.0	00.0	0.00	0.00	0.09	0.11	0.13
Sum	1.00	1.00	1.00	1.00	0.98	1.00	1.06	1.00	1.00	1.00	1.00
${ m Mg}^{2+}$	0.03	0.01	00.00	0.00	0.00	0.03	0.00	0.04	0.00	00.00	00.0
Fe	0.03	0.04	0.07	0.07	00.00	0.00	0.00	0.02	0.06	0.06	0.07
$M_{\tilde{n}_{L}}^{2+}$	0.00	00.00	00.0	00.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca∫	0.85	0.85	0.78	0.78	0.99	0.92	0.86	0.85	0.84	0.86	0.78
Na	0.07	0.08	0.14	0.15	0.03	0.05	0.08	0.08	0.09	0.07	0.14
Sum	0.98	0.98	0.99	1.00	1.02	1.00	0.94	0.99	0.99	0.99	0.99

Table E.1: (Chemi	cal compositi	on of Yogo py	roxenes) coi	ntinued.							
	G7-1	G7-2	G7-3	G7-4	G7-5	G7-6	G7-7	G7-8	G7-9	G7-10	G7-11
	Rim 3	Rim 2	Core	Core	Rim 4	Rim 3	Rim 2	Rim 2	Rim 1	Rim 1	Core
Ca	48.02	49.42	46.15	45.88	52.94	50.83	48.86	49.42	46.15	46.74	46.43
Mg	44.63	43.02	35.50	35.88	31.02	40.88	43.75	43.02	37.91	38.04	35.71
$Fe_{\pm}(1)$	7.34	7.56	18.34	18.24	16.04	8.29	7.39	7.56	15.93	15.22	17.86
· · · · · · · · · · · · · · · · · · ·	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
тв	85.87	85.06	65.93	66.30	65.91	83.15	85.56	85.06	70.41	71.43	66.67
Mg/(Mg+Fe2+)	0.96	0.95	06.0	06.0	1.00	1.00	1.00	0.97	0.92	0.92	06.0
Mg/(Mg+Fer)	0.85	0.85	0.76	0.74	0.66	0.83	0.86	0.84	0.78	0.80	0.78
100Fe2+	3.80	5.19	10.45	10.29	00.00	00.00	00.00	2.78	8.00	7.89	10.45
/(Fe2++Mg)											
100Ca/(Ca+Mg)	52.80	53.80	56.52	56.12	63.06	56.44	52.76	54.84	54.90	55.13	56.52
Name	Aluminian	Aluminian	Aluminian	ı ferrian	Subsilicio	c aluminian	ferrian	Alumir	iian ferroan	ferrian diop	side
	ferroan	diopside	ferroan di	iopside		diopside					
	diopside										
End-members:											
NaFe ^{5t} Si ₂ O	0.070	0.080	0.120	0.140	0.030	0.050	0.080	0.080	060'0	0.070	0.100
NaAlSi,Ó	0.000	0.000	0.020	0.010	0.000	0.000	0.000	0.000	0.000	000.0	0.040
CaTiAIÂIÔ	0.010	0.010	0.020	0.020	090.0	0.030	0.020	0.020	0.020	0.020	0.020
CaFe [*] AlSiÔ ₂	0.030	0.010	0.000	0.000	0.270	0.100	0.050	0.030	0.050	0.040	0.000
CaCrAISiO ₆	0.000	0.000	000.0	0.000	0.000	0.000	0.000	0.010	0.000	000.0	0.000
CaAIAISiO	0.135	0.180	0.120	0.125	0.040	0.105	0.140	0.160	0.065	0.065	0.110
Ca,Si,O, (Wo)	0.338	0.325	0.320	0.318	0.310	0.343	0.325	0.315	0.353	0.368	0.325
Mg Si O (En)	0.395	0.370	0.300	0.305	0.290	0.370	0.385	0.370	0.345	0.350	0.300
Fe Ši Ó (Fs)	0.015	0.020	0.095	0.085	0.000	0.000	0.000	0.010	0.075	0.085	0.100
Total	0.993	0.995	0.995	1.003	1.000	0.998	1.000	0.995	0.998	0.998	0.995
$(1) \operatorname{Fe}_{\mathrm{T}} = \operatorname{Fe}^{3++} \operatorname{Fe}$	2++ Mn2+										

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Table E.1:	(Chemical o	composition (of Yogo pyrc	oxenes) cont	inued.		
	G7-12	G7-13	G10-1	G10-2	G10-3	G10-8	G10-9
	Core	Core	Pyr	oxenes in P	/roxene + Pl	eonaste xenol	lith
SiQ	48.95	48.90	46.83	44.01	45.62	49.60	46.72
, Aj Ó	6.63	6.62	9.14	10.89	90.6	6.94	10.31
FeÓ	6.17	5.97	1.32	00.0	0.37	4.06	4.09
Fe_O	3.55	3.72	3.69	6.15	4.71	0.00	0.57
Tiố,	0.67	0.69	0.86	0.93	1.00	0.62	1.00
ĊŗŐ	00.0	0.01	0.02	0.00	0.30	0.15	0.01
MnO	0.03	0.09	0.05	0.09	0.08	, 0.11	0.07
NiO	0.01	0.03	00.0	0.02	0.00	0.06	0.04
MgO	10.66	10.77	13.22	11.92	12.97	14.33	12.72
CaO	19.24	19.40	22.53	23.52	23.36	22.53	23.33
Na,O	2.00	1.93	0.64	0.50	0.42	00.0	0.00
TÓTAL	97.91	98.13	98.30	98.03	97.89	98.40	98.86
Si	1.86	1.85	1.75	1.66	1.72	1.84	1.74
AlIV	0.14	0.15	0.25	0.34	0.28	0.16	0.26
Sum	2.00	2.00	2.00	2.00	2.00	2.00	2.00
A	0.16	0.15	0.15	0.14	0.12	0.14	0.19
Fe.	0.10	0.11	0.10	0.17	0.13	0.00	0.02
$\mathrm{Ti}_{\mathrm{i}}^{\mathrm{t}}$	0.02	0.02	0.02	0.03	0.03	0.02	0.03
Cr [‡]	0.00	00.00	00.0	0.00	0.01	00'0	0.00
Mg	0.60	0.61	0.73	0.66	0.71	0.79	0.71
Fe ⁻⁺	0.12	0.11	00.00	00.0	0.00	0.05	0.05
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mg ²⁺	0.00	0.00	0.00	0.01	0.02	0.00	0.00
Fe	0.08	0.08	0.04	00.0	0.01	0.08	0.08
Mn_{t}	0.00	0.00	0.00	00.0	00.0	0.00	0.00
Cat	0.78	0.79	06.0	0.95	0.94	06.0	0.93
Na^{\dagger}	0.15	0.14	0.05	0.04	0.03	00.0	0.00
Sum	1.01	1.01	0.99	1.00	1.00	0.98	1.01

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Table E.1: (Chemic	al compositi	on of Yogo	pyroxenes) c	ontinued.			
	G7-12	G7-13	G10-1	G10-2	G10-3	G10-8	G10-9
	Core	Core	Pyrc	oxenes in Py	rroxene + Ple	onaste xenol	ith
Ca	46.43	46.47	50.85	53.07	51.93	49.45	51.96
Mg	35.71	35.88	41.24	37.43	40.33	43.41	39.66
$\operatorname{Fe}_{\mathrm{T}}^{2}(1)$	17.86	17.65	7.91	9.50	7.73	7.14	8.38
Вш	66.67	67.03	83.91	79.76	83.91	85.87	82.56
Mg/(Mg+Fe2+)	0.88	0.88	0.95	1.00	0.99	0.91	06.0
Mg/(Mg+Fer)	0.77	0.76	0.84	0.80	0.84	0.91	0.88
100Fe2+	11.76	11.59	5.19	00.00	1.39	9.20	10.13
/(Fe2++Mg)							
100Ca/(Ca+Mg)	56.52	56.43	55.21	59.01	56.97	53.25	56.71
Name	Aluminia	n ferrian	subsilicic a	luminian	subsilicic	subsilicic :	aluminian
	ferroan c	liopside	ferroan d	liopside	aluminian	ferrioan	liopside
					ternan chromian diopside		
End-members:					•		
NaFe [*] Si _, O ₆	0.100	0.110	0.050	0.040	0.030	0.000	0.000
NaAlSi,Ó	0.050	0.030	0.000	0.000	0.000	000.0	0.000
CaTiAlÂlÔ	0.020	0.020	0.020	0.030	0.030	0.020	0.030
CaFe [*] AlSiÔ ₂	0.000	0.000	0.050	0.130	0.100	0.000	0.020
CaCrAISiO	0.000	0.000	0.000	0.000	0.010	0.000	0.000
CaAIAISiO	0.105	0.115	0.155	0.145	0.115	0.130	0.186
Ca,Si,O, (Wo)	0.328	0.328	0.338	0.323	0.343	0.375	0.347
Mg Si O (En)	0.300	0.305	0.365	0.335	0.365	0.395	0.355
Fe _, Ši _, Ô _, (Fs)	0.100	0.095	0.020	0.000	0.005	0.065	0.065
Total	1.003	1.003	0.998	1.003	0.998	0.985	1.003
(1) $\operatorname{Fe}_{\mathrm{T}} = \operatorname{Fe}^{3++} \operatorname{Fe}^{3-+}$	++ Mn ²⁺						



SCHEMATIC DRAWINGS OF PYROXENES ANALYZED



1 mm diameter pyroxene, fresh but highly fractured





Standard	GSPIN	GSPIN	GPYX	GSPIN	GSPIN	GSPIN	
Sample No	G 1-1	G1-2	G 10-4	G10-5	G 10-6	G 10-7	33A-3A
Description	Sp onPH	Sp onPH	green p	leonaste in p	leonaste +py	/roxene	
				xen	olith		
FeO	11.18	12.33	11.47	12.02	12.75	12.35	10.32
Fe ₂ O ₂	5.21	3.50	5.35	3.83	3.60	3.96	1.07
MgO	19.66	19.26	19.42	19.13	18.78	18.88	20.34
MnO	0.17	0.13	0.11	0.13	0.16	0.13	0.12
TiO ₂	0.13	0.18	0.07	0.04	0.09	0.09	0.05
Cr ₂ O ₂	0.08	0.07	0.00	0.02	0.00	0.00	0.03
Siố	0.08	0.74	0.06	0.04	0.06	0.04	0.03
NiO	0.15	0.13	0.05	0.07	0.08	0.03	0.09
CaO	0.00	0.02	0.01	0.02	0.03	0.04	0.00
ZnO	0.15	0.15	0.00	0.15	0.18	0.00	0.00
Al ₂ O ₂	62.26	61.55	61.85	63.26	63.50	62.70	65.46
V,O,	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TŐŤAL:	99.07	98.06	98.39	98.71	99.23	98.22	97.51
. .							
Fe	1.93	2.14	1.99	2.07	2.19	2.14	1.77
Mg ²⁺	6.03	5.97	6.00	5.88	5.76	5.84	6.21
Al	15.11	15.08	15.12	15.37	15.39	15.34	15.80
Fe	0.81	0.55	0.83	0.59	0.56	0.62	0.16
Mn ²⁺	0.03	0.02	0.02	0.02	0.03	0.02	0.02
Ti	0.02	0.03	0.01	0.01	0.01	0.01	0.01
Cr ³⁺	0.01	0.01	0.00	0.00	0.00	0.00	0.00
Si ⁴⁺	0.02	0.15	0.01	0.01	0.01	0.01	0.01
Ni ²⁺	0.02	0.02	0.01	0.01	0.01	0.01	0.01
Ca ²⁺	0.00	0.00	0.00	0.00	0.01	0.01	0.00
Zn^{2+}	0.02	0.02	0.00	0.02	0.03	0.00	0.00
$Fe^{3+}/Fe^{3+}+Al+Cr$	0.05	0.04	0.05	0.04	0.04	0.04	0.01
$Fe^{2+}/(Fe^{2+} Mg)$	0.24	0.26	0.25	0.26	0.28	0.27	0.22
Mg/Mg+ Fe	0.76	0.74	0.75	0.74	0.72	0.73	0.78
Cr/Cr+Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti/Ti+Cr+Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr O /Fe O	0.02	0.02	0.00	0.01	0.00	0.00	0.03
$M_2O_3/1O_2O_3$ MgO/ Al O	0.32	0.31	0.31	0.30	0.30	0.30	0.31
$T/T_{1}+A_{1}+C_{1}+F_{2}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1, 1, 1, 1, 1, 0, 1, 1, 0	0.00	0.00	0.00	5.00	0.00		

 Table E.2: Chemical composition of Yogo spinels. The formula contents are recalculated on a basis of 32 anions and 24 cations.

Chan Jand							
Standard	22.4.1.4	22.4.1.5	22.4.1.6	22 4 1 7	22 4 1 0	22.4.1.0	22 4 1 10
Sample No	33A1-4	33AI-5	33AI-6	33AI-/	33A1-8	33AI-9	33AI-10
Description			Spinel	rimming sa	pphire		
•							
FeO	10.38	10.62	11.65	10.94	10.66	10.96	11.15
Fe _. O.	3.59	3.28	1.30	2.94	3.70	1.81	3.10
MgO	20.57	20.49	19.88	20.06	20,70	20.63	20.19
MnO	0.13	0.12	0.14	0.13	0.11	0.13	0.16
TiO ₂	0.05	0.05	0.05	0.05	0.06	0.04	0.05
Cr ₂ Õ ₂	0.28	0.06	0.07	0.05	0.28	0.04	0.09
SiÓ	0.04	0.07	0.07	0.04	0.06	0.03	0.06
NiO	0.15	0.10	0.08	0.14	0.13	0.09	0.11
CaO	0.00	0.01	0.01	0.01	0.00	0.00	0.00
ZnO	0.12	0.16	0.12	0.15	0.15	0.13	0.15
Al ₂ O ₃	64.57	64.93	66.06	64.69	65.11	66.82	65.10
V,0,	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TÕTAL:	99.88	99.89	99.43	99.20	100.96	100.68	100.16
2+							
Fe ²⁺	1.75	1.79	1.97	1.86	1.78	1.83	1.88
Mg	6.20	6.17	5.99	6.08	6.18	6.13	6.07
Al_{3+}	15.38	15.45	15.75	15.51	15.36	15.70	15.48
Fe ₂₊	0.55	0.50	0.20	0.45	0.56	0.27	0.47
Mn ⁻	0.02	0.02	0.02	0.02	0.02	0.02	0.03
Ti ₃₊	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cr ₄₊	0.04	0.01	0.01	0.01	0.04	0.01	0.01
Si ₂₊	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Ni 2+	0.02	0.02	0.01	0.02	0.02	0.01	0.02
Ca ₂₊	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.02	0.02	0.02	0.02	0.02	0.02	0.02
$=^{3+}/=^{3+}/(-1)/(-1)$	0.00	0.00	0.01	0.0 0			
Fe^{2+} / Fe^{2+} + Al+Cr	0.03	0.03	0.01	0.03	0.04	0.02	0.03
re / (re + Mg)	0.22	0.22	0.25	0.23	0.22	0.23	0.24
Mg/Mg+ Fe	0.78	0.78	0.75	0.77	0.78	0.77	0.76
	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11/11+Cr+Al	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$U_2 U_3 / Fe_2 U_3$	0.08	0.02	0.05	0.02	0.08	0.02	0.03
$\frac{\text{MgO}}{\text{T}/\text{T}} + \frac{\text{Al}}{2} \frac{\text{O}}{3} + \frac{\text{C}}{2} + \frac{\text{C}}{2}$	0.32	0.32	0.30	0.31	0.32	0.31	0.31
1/11+AI+Cr+Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table E.2: (Chemical composition of Yogo spinels) continued

Standard				Fe-Mg-	Fe-Mg-	Mg-Fe-	Mg-Fe-
				Al	Al	Al	Al
Sample No	33A1-11	33A1-13	33A1-14	25a1-1	25a1-2	25a1-3	25a1-4
Description	Spine	l rimming sa	pphire	Spinel or	n PH; rim	Spinel on	PH, center
A	_		<u> </u>	L			,
FeO	11.67	10.62	10.87	16.73	18.45	11.32	11.64
Fe ₂ O ₂	1.41	3.47	1.30	9.39	6.93	6.88	6.81
MgO	19.93	20.26	20.23	16.39	17.23	19.38	19.34
MnO	0.14	0.11	0.13	0.42	0.40	0.16	0.16
TiO ₂	0.04	0.06	0.03	0.20	0.15	0.10	0.05
Cr ₂ O ₂	0.01	0.34	0.00	0.05	0.03	0.03	0.01
SiÔ	0.25	0.04	0.03	2.06	3.07	0.05	0.07
NiO	0.08	0.18	0.06	0.21	0.25	0.35	0.24
CaO	0.10	0.01	0.00	0.08	0.13	0.00	0.00
ZnO	0.15	0.16	0.12	0.19	0.16	0.13	0.17
Al ₂ O ₃	65.80	64.21	66.01	52.92	55.87	61.11	61.48
V ₂ O ₃	0.00	0.00	0.00	0.04	0.01	0.03	0.03
TÕTAL:	99.58	99.46	98.78	98.66	102.67	99.53	100.01
Fe ²⁺	1 07	1.80	1.84	3 03	3 10	1.05	2.00
$M\alpha^{2+}$	6.00	6.14	6.12	5 20	5 31	5.96	5.00
	15.67	15 38	15 78	13 50	13.60	14.87	14 90
Fe	0.21	0.53	0.20	15.50	1.08	1.07	1.05
Mn ²⁺	0.02	0.02	0.02	0.08	0.07	0.03	0.03
Ti ⁴⁺	0.01	0.01	0.00	0.03	0.02	0.02	0.01
Cr ³⁺	0.00	0.05	0.00	0.01	0.00	0.00	0.00
Si ⁴⁺	0.05	0.01	0.01	0.45	0.63	0.01	0.01
Ni ²⁺	0.01	0.03	0.01	0.04	0.04	0.06	0.04
Ca ²⁺	0.02	0.00	0.00	0.02	0.03	0.00	0.00
Zn^{2+}	0.02	0.02	0.02	0.03	0.02	0.02	0.03
V ³⁺	0.00	0.00	0.00	0.01	0.00	0.00	0.00
$F_{e}^{3+}/F_{e}^{3+}+\Delta_{1+}C_{r}$	0.01	0.03	0.01	0.10	0.07	0.07	0.07
F_{0}^{2+} (F_{0}^{2+} M_{0})	0.01	0.03	0.01	0.10	0.07	0.07	0.07
$M_{\alpha}/M_{\alpha+}$ F_{α}	0.25	0.23	0.23	0.50	0.50	0.25	0.25
$\Gamma_r/\Gamma_r+\Delta 1$	0.75	0.77	0.77	0.04	0.02	0.75	0.75
$T_i/T_i+C_r+\Delta 1$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\Gamma_r \cap \Gamma_r$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$M_2O/\Lambda 1O$	0.01	0.10	0.00	0.00	0.00	0.00	0.00
$T/T_{1+} \Delta 1 \pm C_{r+} \pm C_{r-}^{2+}$	0.30	0.32	0.31	0.31	0.01	0.52	0.01
1/11+MTCITFE	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table E.2: (Chemical composition of Yogo spinels) continued

.

Standard	Mg-Fe-Al	Mg-Fe-Al	Mg-Fe-Al	Mg-Fe-Al	Mg-Fe-Al	Mg-Fe-Al
Description	spinel on	spinel in	spinel in	Al-Mg-Fe	spinel rimmin	ng magnetite
-	PH, center	matrix;	matrix;			
		center	rim			
Sample No	25a1-5	25a2-4	25a2-5	25a2-6	25a2-9	25a2-2
FeO	11.13	8.88	8.69	8.43	8.37	7.85
Fe ₂ O ₃	6.45	5.73	5.49	5.75	5.91	6.71
MgO	20.26	22.02	21.82	22.08	21.85	22.38
MnO	0.12	0.13	0.08	0.11	0.12	0.13
TiO ₂	0.06	0.10	0.10	0.10	0.10	0.08
Cr_2O_3	0.00	0.62	0.59	0.68	0.87	0.15
SiÕ ₂	0.06	0.06	0.07	0.06	0.08	0.07
NiO	0.16	0.17	0.14	0.19	0.11	0.14
CaO	0.03	0.00	0.02	0.00	0.00	0.02
ZnO	0.14	0.07	0.13	0.17	0.10	0.12
Al_2O_3	63.15	64.25	63.60	63.85	62.69	63.49
$V_{2}O_{3}$	0.06	0.04	0.06	0.03	0.04	0.00
TÕŤAL:	101.62	102.07	100.78	101.44	100.23	101.13
E. ²⁺	1.07	1 47	1.40	1 4	1 41	1 21
re No. ²⁺	1.87	1.47	1.46	1.4	1.41	1.31
Mg	6.08	6.5	6.51	0.55	0.57	0.00
AI_{3^+}	14.97	14.99	15.01	14.97	14.90	14.98
re M ²⁺	0.98	0.85	0.83	0.86	0.90	1.01
Min Tri ⁴⁺	0.02	0.02	0.01	0.02	0.02	0.02
11 3 ⁺	0.01	0.01	0.02	0.01	0.02	0.01
Cr	0.00	0.1	0.09	0.11	0.14	0.02
S1 2+	0.01	0.01	0.01	0.01	0.02	0.01
N1 2+	0.03	0.03	0.02	0.03	0.02	0.02
Ca_{2^+}	0.01	0.00	0.00	0.00	0.00	0.00
Zn 3+	0.02	0.01	0.02	0.02	0.01	0.02
V	0.01	0.01	0.01	0.00	0.01	0.00
$Fe^{3+}/Fe^{3+}+Al+Cr$	0.06	0.05	0.05	0.05	0.06	0.06
$Fe^{2+}/(Fe^{2+} Mg)$	0.24	0.18	0.18	0.18	0.18	0.16
$M\sigma/M\sigma + Fe$	0.76	0.82	0.82	0.82	0.82	0.84
Cr/Cr+Al	0.00	0.02	0.00	0.00	0.00	0.00
Ti/Ti+Cr+A1	0.00	0.00	0.00	0.00	0.00	0.00
Cr O /Fe O	0.00	0.11	0.11	0.12	0.15	0.02
$M_{2}O/AIO$	0.32	0.34	0.11	0.35	0.35	0.35
$T/T_{1} + A_{1} + C_{r} + F_{0}$	0.02	0.04	0.00	0.00	0.00	0.00
	0.00	0.00	0.00	0.00	0.00	0.00

Table E.2: (Chemical composition of Yogo spinels) continued

Description			Cr-spine	l in serpenti	ne		
Sample No	31i-1-3	31i-1-3	31i-1-2	31i-1-5	31i-1-6	31i-1-7	31i-1-8
• • • • • • • • • • • • • • • • • • • •							
FeO	15.07	14.57	14.20	14.06	14.35	11.87	13.84
Fe _. O.	7.90	8.35	8.67	9.62	7.96	7.51	7.60
MgO	12.24	12.59	12.57	13.00	12.39	13.71	12.74
MnO	0.14	0.13	0.10	0.10	0.16	0.05	0.13
TiO ₂	0.79	0.76	0.80	0.92	0.81	0.71	0.71
Cr ₂ Õ ₂	51.94	52.18	51.30	44.26	50.32	53.56	53.30
Siố	0.07	0.06	0.04	0.07	0.08	0.08	0.05
NiO	0.14	0.12	0.24	0.08	0.11	0.07	0.07
CaO	0.04	0.02	0.03	0.11	0.27	0.57	0.09
ZnO	0.00	0.07	0.03	0.24	0.05	0.00	0.11
Al ₂ O ₂	10.63	10.48	10.33	15.10	11.37	9.88	9.84
V,0,	0.07	0.06	0.08	0.11	0.14	0.07	0.05
TŐŤAL:	99.02	99.39	98.38	97.67	98.00	98.07	98.54
24							
Fe	3.31	3.19	3.13	3.05	3.17	2.61	3.05
Mg	4.79	4.91	4.95	5.03	4.87	5.37	5.01
	3.29	3.23	3.21	4.62	3.53	3.06	3.06
Fe	1.56	1.64	1.72	1.88	1.58	1.48	1.51
Mn	0.03	0.03	0.02	0.02	0.04	0.01	0.03
Ti	0.16	0.15	0.16	0.18	0.16	0.14	0.14
Cr ₄₊	10.78	10.79	10.71	9.08	10.49	11.12	11.11
Si ⁺ ₂₊	0.02	0.02	0.01	0.02	0.02	0.02	0.01
Ni ²⁺	0.03	0.03	0.05	0.02	0.02	0.02	0.02
Ca	0.01	0.01	0.01	0.03	0.08	0.16	0.03
Zņ	0.00	0.01	0.01	0.05	0.01	0.00	0.02
V	0.02	0.01	0.02	0.02	0.03	0.02	0.01
34 34							
Fe_+ / Fe_+ Al+Cr	0.10	0.10	0.11	0.12	0.10	0.09	0.10
Fe [*] / (Fe [*] + Mg)	0.41	0.39	0.39	0.38	0.39	0.33	0.38
Mg/Mg+ Fe	0.59	0.61	0.61	0.62	0.61	0.67	0.62
Cr/Cr+Al	0.77	0.77	0.77	0.66	0.75	0.78	0.78
Ti/Ti+Cr+Al	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cr_2O_3/Fe_2O_3	6.57	6.25	5.92	4.60	6.32	7.13	7.01
MgO/ Al ₂ O	1.15	1.20	1.22	0.86	1.09	1.39	1.30
T/Ti+Al+Cr+Fe ²⁺	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Table E.2: (Chemical composition of Yogo spinels) continued

Standard							
Sample No	25a3-1	25a3-2	25a3-3	G 9-1	G9-2	G9-3	G 9-4
Description	Cr-spinel in	n weathered	pyroxene	magnetite	magnetite	magnetite	magnetite
FeO	8.11	13.76	13.78	34.63	33.46	37.26	35.00
Fe ₂ O ₂	14.40	7.89	7.83	50.13	51.23	44.49	49.29
MgO	17.35	12.27	13.26	0.13	0.14	0.12	0.12
MnO	0.17	0.10	0.11	0.10	0.13	0.13	0.08
TiO ₂	0.81	0.66	0.73	1.76	1.41	4.18	1.67
Cr ₂ O ₂	45.18	53.41	47.30	0.04	0.05	0.16	0.23
SiÔ	0.94	0.09	0.29	3.69	3.11	4.03	4.04
NiO	0.10	0.13	0.21	0.12	0.11	0.12	0.14
CaO	1.82	0.38	0.25	0.35	0.49	0.32	0.34
ZnO	0.11	0.16	0.15	0.30	0.37	0.25	0.26
Al ₂ O ₃	14.42	8.84	14.53	1.74	2.63	1.56	1.63
V,0,	0.08	0.11	0.12				
TŐŤAL:	103.49	97.80	98.57	92.99	93.13	92.62	92.80
2							
Fe	1.63	3.08	2.96	9.30	8.95	10.01	9.41
Mg	6.2	4.89	5.09	0.06	0.07	0.06	0.06
Al	4.08	2.79	4.41	0.66	0.99	0.59	0.62
Fe	2.6	1.59	1.52	12.11	12.33	10.76	11.92
Mn	0.03	0.02	0.02	0.03	0.04	0.04	0.02
Ti	0.15	0.13	0.14	0.42	0.34	1.01	0.40
Cr	8.57	11.29	9.62	0.01	0.01	0.04	0.06
Si	0.23	0.02	0.07	1.18	0.99	1.29	1.30
Ni ²⁺	0.02	0.03	0.04	0.03	0.03	0.03	0.04
Ca ²⁺	0.47	0.11	0.07	0.12	0.17	0.11	0.12
Zņ	0.02	0.03	0.03	0.07	0.09	0.06	0.06
V ³⁺	0.02	0.02	0.02				
21 21							
Fe , Fe + Al+Cr	0.17	0.10	0.10	0.95	0.92	0.94	0.95
$Fe^{2^{+}}/(Fe^{2^{+}}+Mg)$	0.21	0.39	0.37	0.99	0.99	0.99	0.99
Mg/Mg+ Fe ²⁺	0.79	0.61	0.63	0.01	0.01	0.01	0.01
Cr/Cr+Al	0.68	0.80	0.69	0.01	0.01	0.06	0.09
Ti/Ti+Cr+Al	0.01	0.01	0.01	0.39	0.25	0.62	0.37
Cr_0 , /Fe ₀	3.14	6.77	6.04	0.00	0.00	0.00	0.00
MgO/ Al Ó	1.20	1.39	0.91	0.07	0.05	0.08	0.07
T/Ti+Al+Cr+Fe ²⁺	0.01	0.01	0.01	0.04	0.03	0.09	0.04

Table E.2: (Chemical composition of Yogo spinels) continued

Standard	•			MAY 7	MAY 6	MAY 7	MAY 7
Sample No	G 9-5	G 9-6	G9-7	31i-2-1	31i-2-1	31i-2-1	31i-2-2
Description	magnetite	magnetite	magnetite	magnetite	magnetite	magnetite	magnetite
				in matrix	in matrix	in matrix	in matrix
FeO	34.01	35.31	35.06	33.34	35.13	26.82	31.74
Fe ₂ O ₃	50.47	48.70	48.39	33.57	46.68	33.49	53.73
MgO	0.12	0.15	0.13	4.86	1.99	4.54	0.93
MnO	0.16	0.11	0.12	0.21	0.26	0.87	1.04
TiO ₂	2.16	2.25	2.18	1.06	1.10	1.29	2.02
Cr ₂ O ₃	0.15	0.06	0.09	1.94	2.05	15.74	0.20
SiÕ	2.78	3.69	3.67	8.58	5.60	1.06	1.15
NiO	0.02	0.03	0.03	0.09	0.12	0.04	0.00
CaO	0.36	0.31	0.36	0.39	0.44	0.20	0.32
ZnO	0.34	0.28	0.20	0.34	0.29	0.24	0.30
Al ₂ O ₃	2.63	2.21	2.23	6.56	3.51	12.57	6.18
V,0,				0.07	0.12	0.16	0.25
TÕTAL:	93.20	93.10	92.46	91.01	97.28	97.02	97.86
Fe ²⁺	9.10	9.44	9.43	8.36	8.73	6.33	7.95
Mg ²⁺	0.06	0.07	0.06	2.17	0.88	1.91	0.42
Al	0.99	0.83	0.85	2.32	1.23	4.18	2.18
Fe	12.15	11.71	11.72	7.58	10.44	7.12	12.11
Mn ²⁺	0.04	0.03	0.03	0.05	0.07	0.21	0.26
Ti	0.52	0.54	0.53	0.24	0.25	0.27	0.46
Cr	0.04	0.02	0.02	0.46	0.48	3.52	0.05
Si	0.89	1.18	1.18	2.57	1.66	0.30	0.34
Ni	0.01	0.01	0.01	0.02	0.03	0.01	0.00
Ca	0.12	0.11	0.12	0.13	0.14	0.06	0.10
Zn^{2+}	0.08	0.07	0.05	0.08	0.06	0.05	0.07
V^{3+}				0.02	0.03	0.04	0.06
$Fe^{3+}_{1}/Fe^{3+}+Al+Cr$	0.92	0.93	0.93	0.73	0.86	0.48	0.84
$Fe^{2+}/(Fe^{2+}+Mg)$	0.99	0.99	0.99	0.79	0.91	0.77	0.95
Mg/Mg+ Fe	0.01	0.01	0.01	0.21	0.09	0.23	0.05
Cr/Cr+Al	0.04	0.02	0.02	0.17	0.28	0.46	0.02
Ti/Ti+Cr+Al	0.34	0.39	0.38	0.08	0.13	0.03	0.17

Table E.2: (Chemical composition of Yogo spinels) continued

0.00

0.05

0.05

0.00

0.07

0.05

0.00

0.06

0.05

0.06

0.74

0.02

0.04

0.57

0.02

0.47

0.36

0.02

0.00

0.15

0.04

 $\frac{\text{Cr}_2\text{O}_3/\text{Fe}_2\text{O}_3}{\text{MgO}/\text{Al}_2\text{O}_3}$ $\frac{\text{T/Ti}+\text{Al}+\text{Cr}+\text{Fe}^{2+}}{\text{T/Ti}+\text{Al}+\text{Cr}+\text{Fe}^{2+}}$

Standard	MAY 6	MAY 6	MAY 6	MAY 6	MAY 7	MAY 6	MAY 7
Sample No	31i-2-2	31I-1	31I-2	31I-3	31i-4	31I-5	31i-6
Description	magnetite						
	in matrix						
FeO	31.76	28.90	31.88	29.16	28.71	32.96	29.10
Fe ₂ O ₂	57.47	55.46	50.11	57.47	57.16	56.16	54.31
MgO	0.63	2.79	2.08	1.78	2.67	0.20	2.31
MnO	1.14	1.16	0.71	1.36	1.06	1.90	1.19
TiO ₂	2.53	2.36	2.02	1.93	2.00	5.08	1.71
Cr ₂ O ₂	0.45	0.00	0.05	0.04	0.00	0.00	0.05
SiŐ	0.59	0.10	2.43	0.09	0.13	0.14	0.73
NiO	0.09	0.09	0.03	0.11	0.07	0.05	0.04
CaO	0.29	0.13	0.36	0.18	0.18	0.18	0.32
ZnO	0.15	0.22	0.17	0.17	0.17	0.28	0.14
Al ₂ O ₂	3.54	8.42	6.81	6.41	7.42	1.21	7.96
V ₂ O ₂	0.22	0.27	0.27	0.25	0.29	0.37	0.22
TŐŤAL:	98.84	99.90	96.92	98.97	99.84	98.53	98.08
a .							
Fe	8.03	6.95	7.91	7.21	6.95	8.5	7.14
Mg	0.28	1.2	0.92	0.78	1.15	0.09	1.01
Al	1.26	2.85	2.38	2.23	2.53	0.44	2.75
Fe	13.07	12.00	11.20	12.79	12.46	13.03	12.00
Mn	0.29	0.28	0.18	0.34	0.26	0.50	0.30
Ti	0.58	0.51	0.45	0.43	0.44	1.18	0.38
Cr ³⁺	0.11	0.00	0.01	0.01	0.00	0.00	0.01
Si	0.18	0.03	0.72	0.03	0.04	0.04	0.21
Ni	0.02	0.02	0.01	0.03	0.02	0.01	0.01
Ca ²⁺	0.09	0.04	0.11	0.06	0.06	0.06	0.10
Zņ	0.03	0.05	0.04	0.04	0.04	0.06	0.03
V	0.05	0.06	0.06	0.06	0.07	0.09	0.05
21 21							
Fe / Fe + Al+Cr	0.91	0.81	0.82	0.85	0.83	0.97	0.81
$Fe^{2+}/(Fe^{2+}+Mg)$	0.97	0.85	0.90	0.90	0.86	0.99	0.88
Mg/Mg+ Fe ²⁺⁻	0.03	0.15	0.10	0.10	0.14	0.01	0.12
Cr/Cr+Al	0.08	0.00	0.00	0.00	0.00	0.00	0.00
Ti/Ti+Cr+Al	0.30	0.15	0.16	0.16	0.15	0.73	0.12
Cr_0 , /Fe ₀	0.01	0.00	0.00	0.00	0.00	0.00	0.00
MgO/ Al O	0.18	0.33	0.31	0.28	0.36	0.16	0.29
$T/Ti+Al+Cr+Fe^{2+}$	0.06	0.05	0.04	0.04	0.04	0.12	0.04
			•		•		

Table E.2: (Chemical composition of Yogo spinels) continued

Standard	MAY 7	MAY 6	MAY 6	MAY 7	MAY 6	MAY 6	MAY 6
Sample No	31i-7	31I-8	31I-9	31i-10	31I-11	31 I- 12	25a-1
Description	magnetite	magnetite	magnetite	magnetite	magnetite	magnetite	magnetite
-	in matrix	in matrix					
FeO	35.88	31.08	35.42	39.52	33.15	29.23	30.63
Fe ₂ O ₂	50.64	54.14	51.17	44.42	57.66	55.87	60.59
MgO	0.23	1.12	0.36	0.30	0.22	2.40	0.07
MnO	0.25	1.08	0.22	0.15	0.26	1.30	2.03
TiO ₂	1.31	1.70	1.10	1.09	2.26	2.17	2.84
Cr ₂ O ₃	0.09	0.01	0.08	0.06	0.20	0.01	0.01
SiÔ	4.33	1.07	3.98	7.12	1.21	0.12	0.20
NiO	0.05	0.08	0.06	0.10	0.07	0.00	0.05
CaO	0.45	0.33	0.42	0.46	0.29	0.14	0.11
ZnO	0.26	0.18	0.13	0.23	0.11	0.18	0.36
Al ₂ O ₃	2.49	6.68	3.29	2.85	1.83	8.13	0.54
V ₂ O ₃	0.22	0.30	0.26	0.19	0.12	0.22	0.17
TÕTAL:	96.19	97.76	96.50	96.48	97.37	99.77	97.59
2+							
Fe	9.25	7.76	9.07	10.00	8.59	7.07	8.03
Mg	0.11	0.5	0.16	0.14	0.1	1.03	0.03
Al	0.90	2.35	1.19	1.02	0.67	2.77	0.2
Fe	11.74	12.17	11.79	10.12	13.45	12.16	14.29
Mn	0.07	0.27	0.06	0.04	0.07	0.32	0.54
Ti	0.30	0.38	0.25	0.25	0.53	0.47	0.67
Cr ³⁺	0.02	0.00	0.02	0.01	0.05	0.00	0.00
Si	1.33	0.32	1.22	2.16	0.38	0.03	0.06
Ni	0.01	0.02	0.01	0.02	0.02	0.00	0.01
Ca	0.15	0.11	0.14	0.15	0.1	0.04	0.04
Zņ	0.06	0.04	0.03	0.05	0.03	0.04	0.08
V^{3^+}	0.05	0.07	0.06	0.05	0.03	0.05	0.04
21 21							
Fe [*] /Fe [*] +Al+Cr	0.93	0.84	0.91	0.91	0.95	0.81	0.99
$Fe^{2+}/(Fe^{2+}+Mg)$	0.99	0.94	0.98	0.99	0.99	0.87	1.00
Mg/Mg+ Fe ²⁺	0.01	0.06	0.02	0.01	0.01	0.13	0.00
Cr/Cr+Al	0.02	0.00	0.02	0.01	0.07	0.00	0.00
Ti/Ti+Cr+Al	0.25	0.14	0.17	0.20	0.42	0.15	0.77
Cr_0 , /Fe ₀	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO/ Al_O	0.09	0.17	0.11	0.10	0.12	0.30	0.14
$T/Ti+Al+Cr+Fe^{2+}$	0.03	0.04	0.02	0.02	0.05	0.05	0.08

Table E.2: (Chemical composition of Yogo spinels) continued

Standard	MAY 6	MAY 6	MAY 7	MAY 6	MAY 6	MAY 7	MAY 6
Sample No	25a-2	25a-3	25a-3	25a-4	25a-5	25a-5	25a-6
Description	magnetite	magnetite	magnetite	magnetite	magnetite	magnetite	magnetite
	in matrix	in matrix	in matrix	in matrix	in matrix	in matrix	in matrix
					•••••		•••
FeO	30.21	29.21	29.59	30.26	29.99	29.13	29.46
Fe ₂ O ₃	63.73	62.29	57.20	53.91	55.85	53.23	51.80
MgO	0.33	1.48	1.64	1.28	0.89	2.13	1.88
MnO	1.61	1.03	1.03	0.78	1.53	1.47	1.24
T_1O_2	1.46	1.57	1.60	1.76	2.21	2.22	2.30
$\operatorname{Cr}_{2}O_{3}$	0.02	0.04	0.03	0.06	0.00	0.03	0.01
SIO ₂	0.10	0.11	0.27	0.63	0.16	0.08	0.32
NIO ·	0.00	0.02	0.00	0.13	0.02	0.03	0.08
CaO	0.07	0.15	0.10	0.12	0.20	0.19	0.14
ZnO	0.18	0.03	0.14	0.17	0.31	0.15	0.24
Al ₂ O ₃	1.48	2.69	6.27	6.64	5.74	9.28	8.79
V_2O_3	0.19	0.23	0.26	0.26	0.30	0.29	0.28
TOTAL:	99.39	98.85	98.11	95.98	97.19	98.23	96.54
F ²⁺		- 40			5 (0)	Z 10	7 0 5
Fe 2+	7.74	7.40	7.39	7.70	7.62	7.12	7.35
Mg	0.15	0.67	0.73	0.58	0.40	0.93	0.84
Al ₃₊	0.53	0.96	2.21	2.38	2.05	3.20	3.09
Fe 2+	14.68	14.19	12.85	12.35	12.77	11.71	11.62
Mn T ⁴⁺	0.42	0.26	0.26	0.20	0.39	0.36	0.31
T1 3+	0.34	0.36	0.36	0.40	0.50	0.49	0.52
Cr	0.00	0.01	0.01	0.01	0.00	0.01	0.00
S1 2+	0.03	0.03	0.08	0.19	0.05	0.02	0.10
Ni 2+	0.00	0.00	0.00	0.03	0.00	0.01	0.02
Ca_{2^+}	0.02	0.05	0.03	0.04	0.07	0.06	0.04
Zn 3+	0.04	0.01	0.03	0.04	0.07	0.03	0.05
V	0.05	0.06	0.06	0.06	0.07	0.07	0.07
3+3+							
Fe_{2+}/Fe_{2+} +Al+Cr	0.97	0.94	0.85	0.84	0.86	0.78	0.79
$Fe^{-} / (Fe^{-} + Mg)$	0.98	0.92	0.91	0.93	0.95	0.88	0.90
Mg/Mg+ Fe	0.02	0.08	0.09	0.07	0.05	0.12	0.10
Cr/Cr+Al	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Ti/Ti+Cr+Al	0.39	0.27	0.14	0.14	0.20	0.13	0.14
Cr_2O_3/Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO/Al ₂ O ₃	0.22	0.55	0.26	0.19	0.15	0.23	0.21
T/Ti+Al+Cr+Fe ²⁺	0.04	0.04	0.04	0.04	0.05	0.05	0.05

Table E.2: (Chemical composition of Yogo spinels) continued

,

Standard	MAY 7	MAY 7	MAY 6	MAY 6	MAY 6	MAY 7
Sample No	25a5-5	25a2-1	25a2-2	25a2-3	25a5-2	25a5-2
Description	magnetite		magnetite	rimming mat	rix pleonaste	•
•	in matrix					
FeO	35.64	38.63	29.93	30.93	39.14	38.20
Fe ₂ O ₃	44.23	35.33	57.68	48.89	22.41	27.28
MgO	1.14	0.54	1.16	1.92	0.27	0.37
MnO	0.73	0.12	1.26	0.81	0.07	0.10
TiO ₂	1.71	1.01	1.78	2.47	4.09	3.24
Cr ₂ O ₃	0.03	0.77	0.07	0.04	0.24	0.06
SiO ₂	4.47	7.20	0.20	1.50	4.99	5.03
NiO	0.07	0.20	0.12	0.10	0.18	0.13
CaO	0.26	0.35	0.06	0.17	0.44	0.48
ZnO	0.09	0.53	0.16	0.52	0.57	0.52
Al_2O_3	7.22	7.76	5.40	11.36	16.07	14.01
$V_2 O_3$	0.26	0.13	0.28	0.31	0.25	0.28
TÕŤAL:	95.84	92.55	98.08	94.02	88.70	89.69
Fo ²⁺	8 01	0.87	7 51	7 75	10.01	0 70
1 ⁻ e Ma	0.51	9.07	0.52	0.86	0.12	9.79 0.1 7
Λ1	0.51	2.20	1.02	0.80	5 70	5.06
Fo ³⁺	2.54	2.00	1.92	4.01	5.15	6.20
Nn ²⁺	9.95	0.12	0.32	9.09	0.02	0.03
	0.19	0.05	0.32	0.21	0.02	0.05
$\frac{1}{3^{+}}$	0.08	0.25	0.4	0.00	0.94	0.75
Si ⁴⁺	1 34	2 20	0.02	0.45	1.53	1 54
Ni ²⁺	0.02	0.05	0.00	0.45	0.04	0.03
C_{2}^{2+}	0.02	0.05	0.03	0.02	0.14	0.05
$7n^{2+}$	0.00	0.11	0.02	0.05	0.14	0.10
V^{3+}	0.02	0.12	0.04	0.12	0.15	0.12
v	0.00	0.05	0.07	0.07	0.00	0.07
$Fe^{3+}/Fe^{3+}+Al+Cr$	0.80	0.73	0.87	0.71	0.47	0.55
$Fe^{2+}/(Fe^{2+}+Mg)$	0.95	0.98	0.94	0.90	0.99	0.98
Mg/Mg+ Fe ²⁺	0.05	0.02	0.06	0.10	0.01	0.02
Cr/Cr+Al	0.00	0.06	0.01	0.00	0.01	0.00
Ti/Ti+Cr+Al	0.13	0.07	0.17	0.12	0.14	0.13
Cr ₀ , /Fe ₀	0.00	0.02	0.00	0.00	0.01	0.00
$M_{g}^{2}O/Al_{s}^{2}O_{s}^{3}$	0.16	0.07	0.22	0.17	0.02	0.03
$T/Ti+Al+Cr+Fe^{2+3}$	0.03	0.02	0.04	0.05	0.06	0.05
		2. 	0.0.			

Table E.2: (Chemical composition of Yogo spinels) continued

Standard	MAY 6	MAY 7	MAY 6	MAY 7	MAY 6	MAY 7
Sample No	25a5-3	25a5-3	25a5-4	25a5-4	31i-5-1	31i-5-1
Description	magnetite	rimming ma	trix pleonast	e	magnetit	te rimming
					pleor	naste in
				······································	phlo	gopite
БQ	24.55	20.41	06.55	29.05	27.00	20 62
FeO	34.55	39.41	20.55	28.95	27.88	38.52
$\operatorname{Fe}_{2}O_{3}$	34.70	22.08	53.09	49.19	2 5 5	43.29
MgO	1.30	0.40	J.40	4.19	3.33	0.31
	0.44	0.04	0.78	0.71	0.90	0.10
10_2	2.91	3.99	2.08	2.79	1.98	0.90
	0.07	5.71	0.04	0.00	0.02	6.55
SIO_2	0.13	5.71	0.13	0.99	0.13	0.55
	0.13	0.04	0.00	0.12	0.00	0.03
CaO 7n0	0.44	0.45	0.07	0.12	0.05	0.35
	11.66	0.89 14 77	11 14	10.00	0.04 8.40	2.82
X_{2}^{0}	0.36	0.22	0.28	0.25	0.45	0.27
	0.50 00.01	88.63	100.95	0.25	0.25	95.61
IUIAL.	90.91	00.00	100.95	90.55	<i></i>	22.01
Fe ²⁺	8.84	10.12	6.12	6.87	6.69	9.86
Mg ²⁺	0.62	0.18	2.24	1.77	1.52	0.14
Al	4.20	5.35	3.62	3.67	2.87	1.02
Fe	7.99	5.24	11.13	10.50	12.14	10.44
Mn	0.11	0.01	0.18	0.17	0.22	0.04
Ti	0.67	0.92	0.56	0.60	0.43	0.22
Cr ₁ ³⁺	0.02	0.01	0.01	0.01	0.00	0.03
Si	1.18	1.75	0.04	0.28	0.04	2.01
Ni_{2+}^{2+}	0.03	0.01	0.01	0.03	0.01	0.01
Ca	0.14	0.15	0.02	0.04	0.02	0.12
Zņ	0.10	0.20	0.02	0.00	0.01	0.06
V ³⁺	0.09	0.05	0.06	0.06	0.06	0.07
3+ 3+						
Fe_/ Fe_+Al+Cr	0.65	0.49	0.75	0.74	0.81	0.91
Fe' / (Fe' + Mg)	0.93	0.98	0.73	0.80	0.81	0.99
Mg/Mg+ Fe	0.07	0.02	0.27	0.20	0.19	0.01
Cr/Cr+Al	0.00	0.00	0.00	0.00	0.00	0.03
Ti/Ti+Cr+Al	0.14	0.15	0.13	0.14	0.13	0.17
Cr_2O_3/Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.00
MgO/Al ₂ O ₃	0.12	0.03	0.49	0.38	0.42	0.11
T/Ti+Al+Cr+Fe ²⁺	0.05	0.06	0.05	0.05	0.04	0.02

Table E.2: (Chemical composition of Yogo spinels) continued

Standard	MAY 6	MAY 6	MAY 6	MAY 7
Sample No	31i-5-2	31i-2-5	31i-2-7	31i-2-7
Description	magnetite	magne	tite rimming	sapphire
	rimming			
	pleonaste			
	in PH			
FaO	38 13	27 10	27.03	28.22
Fe O	45 59	50.58	50.46	49 38
$M_{2}O_{3}$	0.36	5 14	4 44	4 10
MnO	0.15	0.07	1 09	0.99
TiOn	1.13	2.72	1.79	1.93
Cr.O.	0.11	0.06	0.46	0.56
SiO ² 3	6.25	0.33	0.09	1.66
NiO ²	0.09	0.11	0.09	0.13
CaO	0.34	0.02	0.07	0.08
ZnO	0.28	0.15	0.19	0.19
Al ₂ O ₂	2.87	12.29	14.14	9.80
V,0,	0.27	0.25	0.16	0.21
TÔTAL:	95.57	99.46	100.01	97.24
2+				
Fe ₂₊	9.78	6.3	6.24	6.80
Mg	0.16	2.13	1.83	1.76
Al3+	1.04	4.03	4.6	3.33
Fe ₂₊	10.52	10.58	10.47	10.70
Mn	0.04	0.17	0.25	0.24
11 ₃₊	0.26	0.57	0.37	0.42
Cr 2: ⁴⁺	0.03	0.01	0.10	0.13
S1	1.92	0.09	0.02	0.48
IN1 C- ²⁺	0.02	0.02	0.02	0.03
$Ca_{2^{+}}$	0.11	0.01	0.02	0.02
$\sum_{v=1}^{2^{+}}$	0.06	0.03	0.04	0.04
V	0.07	0.06	0.04	0.05
$Fe^{3+}/Fe^{3+}+Al+Cr$	0.91	0.72	0.69	0.76
$Fe^{2+}/(Fe^{2+}+Mg)$	0.98	0.75	0.77	0.79
Mg/Mg+ Fe ²⁺⁰	0.02	0.25	0.23	0.21
Cr/Cr+Al	0.03	0.00	0.02	0.04
Ti/Ti+Cr+Al	0.20	0.12	0.07	0.11
Cr ₂ O ₂ /Fe ₂ O ₂	0.00	0.00	0.01	0.01
MgO/ Al Ó	0.13	0.42	0.31	0.42
T/Ti+Al+Cr+Fe ²⁺	0.02	0.05	0.03	0.04

Table E.2: (Chemical composition of Yogo spinels) continued
Sample	phla	PH1	ph1b	PH1B	PH2a	PH2b	PH4a	PH4b
<u>.</u>	mat	rix phlogop	ite	mat	rix phlogop	ite	matrix p	hlogopite
SiO ₂	34.06	33.86	34.20	34.59	33.33	32.85	33.24	32.97
Al_2O_3	17.04	17.07	16.92	17.13	16.67	16.96	16.95	18.26
FeO	8.28	8.15	8.54	8.43	7.80	7.78	8.08	7.53
MgO	18.54	18.61	19.11	19.08	18.39	18.40	18.61	17.20
TiO ₂	3.29	3.31	2.79	2.91	3.70	3.85	3.42	3.87
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MnO	0.13	0.07	0.13	0.13	0.06	0.11	0.07	0.10
Na_20	0.43	0.45	0.47	0.46	0.42	0.46	0.46	0.35
K ₂ O	8.33	8.36	8.65	8.65	8.10	7.95	8.14	7.39
CaO	0.12	0.11	0.13	0.02	0.07	0.04	0.06	0.06
BaO	3.90	3.87	3.03	3.00	4.52	4.84	4.10	5.29
F	0.72	0.66	0.76	0.62	0.74	0.75	0.66	0.70
O=F	-0.30	-0.28	-0.32	-0.26	-0.31	-0.32	-0.28	-0.29
TOTAL	94.83	94.50	94.75	95.02	93.81	93.99	93.79	93.72
Si ⁴⁺	5.12	5.10	5.12	5.16	5.08	5.01	5.06	5.02
Al ³⁺	2.88	2.90	2.88	2.84	2.92	2.99	2.94	2.98
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al ³⁺	0.14	0.13	0.10	0.17	0.08	0.06	0.10	0.30
Fe ²⁺	1.04	1.03	1.11	1.05	0.99	0.99	1.03	0.96
Mg ²⁺	4.15	4.18	4.26	4.24	4.18	4.19	4.22	3.91
Ti ⁴⁺	0.37	0.38	0.31	0.33	0.42	0.44	0.39	0.44
Cr ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mn ²⁺	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.01
	5.58	5.60	5.70	5.64	5.60	5.63	5.65	5.32
K ⁺	1.60	1.61	1.65	1.64	1.58	1.55	1.58	1.44
Ca ²⁺	0.02	0.02	0.02	0.00	0.01	0.01	0.01	0.01
Ba ²⁺	0.23	0.23	0.18	0.18	0.27	0.29	0.24	0.32
Na ⁺	0.13	0.13	0.14	0.13	0.12	0.14	0.14	0.10
	1.98	1.99	1.99	1.95	1.98	1.99	1.97	1.87
F ⁻	0.34	0.31	0.36	0.29	0.36	0.36	0.32	0.34
O ²⁻	21.66	21.69	21.64	21.71	21.64	21.64	21.68	21.66
Cat sum	15.70	15.72	15.79	15.76	15.66	15.68	15.72	15.49
Mg/(Mg+Fe)	0.80	0.80	0.79	0.80	0.81	0.81	0.80	0.80
Fe/(Fe+Mg)	0.20	0.20	0.21	0.20	0.19	0.19	0.20	0.20

Table E.3: Chemical composition of Yogo phlogopite

Sample	PH4c	PH4D1	PH4E1	PH4F1	PH4F2	PH4G1	PH7A	PH7A2
	matrix phlogopite	core of	matrix phlo	ogopite	core of phlog	matrix opite	rim of phlog	matrix 30pite
SiO ₂	34.98	33.20	35.01	34.95	33.96	34.82	33.87	33.59
Al ₂ O ₃	16.53	17.18	16.76	16.88	16.89	17.47	16.89	17.44
FeO	8.04	8.13	7.94	7.97	8.58	8.22	8.25	7.95
MgU	19.27	18.04	19.20	19.20	18.88	18.46	18.55	18.21
ΠO_2	3.23	4.09	3.26	3.03	3.23	3.23	2.03	3.58
Cr_2O_3	0.00	0.00	0.04	0.00	0.00	0.03	0.04	0.01
MnO	0.03	0.06	0.14	0.11	0.11	0.16	0.07	0.11
Na_20	0.46	0.31	0.44	0.47	0.47	0.46	0.50	0.44
K ₂ O	8.45	7.92	8.44	8.59	8.54	8.22	8.58	7.70
CaO	0.02	0.04	0.00	0.04	0.01	0.03	1.55	0.08
BaO	3.66	5.55	3.54	3.36	3.51	3.52	2.75	5.10
F	0.68	0.87	0.73	0.87	0.66	0.74	0.75	0.78
O=F	-0.29	-0.37	-0.37	-0.37	-0.28	-0.31	-0.32	-0.33
TOTAL	95.33	95.38	95.50	95.46	94.83	95.36	94.44	94.98
C:4+	5 20	5.02	5 10	5 10	5 10	5 17	5 10	5.06
51 A1 ³⁺	3.20	2.02	2.19	2.10	2.00	2.17	2.10	2.00
AI	2.80	2.90	2.01	2.62	2.90	2.03	2.90	2.94
A 1 ³⁺	0.10	0.00	0.12	0.13	8.00	0.00	0.00	0.16
F_{0}^{2+}	0.10	1.02	0.12	0.13	0.09	1.02	1.04	1.00
Γe $M a^{2+}$	1.00	1.05	0.98	0.99	1.08	1.02	1.04	1.00
1VIg T: ⁴⁺	4.27	4.00	4.23	4.24	4.23	4.00	4.10	4.09
Cr^{3+}	0.30	0.40	0.30	0.34	0.37	0.30	0.30	0.41
Mn^{2+}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Т VШ Т	5.63	5.56	0.02	5.59	5.60	5.49	5.51	5.51
V^+	J.03	1.52	5.01	5.58	5.09	J.40 1.56	1.65	J.JI 1 49
Γ_{-2+}	1.00	1.55	1.60	1.03	1.04	1.50	1.05	1.40
$Ca = D_{2}^{2+}$	0.00	0.01	0.00	0.01	0.00	0.00	0.25	0.01
Da Na ⁺	0.21	0.00	0.21	0.20	0.21	0.20	0.10	0.30
Na	0.13	0.09	0.13	0.14	0.14	0.13	0.15	0.13
-	1.94	1.96	1.94	1.98	1.99	1.89	2.21	1.92
F o ²	0.32	0.42	0.34	0.41	0.31	0.35	0.36	0.37
02	21.68	21.58	21.66	21.59	21.69	21.65	21.64	21.63
Cat sum	15.67	15.60	15.67	15.69	15.77	15.60	15.82	15.59
Mg/(Mg+Fe)	0.81	0.80	0.81	0.81	0.80	0.80	0.80	0.80
Fe/(Fe+Mg)	0.19	0.20	0.19	0.19	0.20	0.20	0.20	0.20

Table E.3: (Chemical composition of Yogo phlogopite) continued.

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$\begin{array}{c} & & & \\ SiO_2 & 34.0 \\ Al_2O_3 & 17.2 \\ FeO & 7.4 \\ MgO & 18.0 \\ TiO_2 & 3.8 \\ Cr_2O_3 & 0.0 \\ MnO & 0.0 \\ Na_2O & 0.4 \\ K_2O & 7.9 \\ R_2O & $	re of matrix ph 0 34.68 2 17.00 7 8.30 8 18.87 0 2.66 0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	34.08 16.67 7.30 19.05 3.63 0.00 0.08 0.45 8.12 0.07	matrix PH 33.96 17.42 8.32 18.84 3.04 0.01 0.13 0.49 8.28	33.42 17.00 7.73 18.63 3.90 0.02 0.07 0.44	core of m 38.53 15.91 4.81 22.09 2.13 0.75 0.09 0.47	38.15 16.17 5.11 21.67 2.12 0.29 0.07	38.52 15.77 4.57 21.82 2.15 0.73 0.05
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	0 34.68 2 17.00 7 8.30 8 18.87 0 2.66 0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	34.08 16.67 7.30 19.05 3.63 0.00 0.08 0.45 8.12 0.07	33.96 17.42 8.32 18.84 3.04 0.01 0.13 0.49 8.28	33.42 17.00 7.73 18.63 3.90 0.02 0.07 0.44	38.53 15.91 4.81 22.09 2.13 0.75 0.09 0.47	38.15 16.17 5.11 21.67 2.12 0.29 0.07	38.52 15.77 4.57 21.82 2.15 0.73 0.05
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	0 34.08 2 17.00 7 8.30 8 18.87 0 2.66 0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	16.67 7.30 19.05 3.63 0.00 0.08 0.45 8.12 0.07	17.42 8.32 18.84 3.04 0.01 0.13 0.49 8.28	17.00 7.73 18.63 3.90 0.02 0.07 0.44	15.91 4.81 22.09 2.13 0.75 0.09 0.47	16.17 5.11 21.67 2.12 0.29 0.07	15.77 4.57 21.82 2.15 0.73 0.05
Ai_2O_3 17.2 FeO 7.4 MgO 18.0 TiO ₂ 3.8 Cr ₂ O ₃ 0.0 MnO 0.0 Na ₂ O 0.4 K ₂ O 7.9	2 17.00 7 8.30 8 18.87 0 2.66 0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	7.30 19.05 3.63 0.00 0.08 0.45 8.12 0.07	8.32 18.84 3.04 0.01 0.13 0.49 8.28	7.73 18.63 3.90 0.02 0.07 0.44	4.81 22.09 2.13 0.75 0.09 0.47	5.11 21.67 2.12 0.29 0.07	4.57 21.82 2.15 0.73 0.05
reo 7.4 MgO 18.0 TiO ₂ 3.8 Cr ₂ O ₃ 0.0 MnO 0.0 Na ₂ 0 0.4 K ₂ O 7.9	7 8.30 8 18.87 0 2.66 0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	19.05 3.63 0.00 0.08 0.45 8.12 0.07	8.32 18.84 3.04 0.01 0.13 0.49 8.28	18.63 3.90 0.02 0.07 0.44	4.81 22.09 2.13 0.75 0.09 0.47	21.67 2.12 0.29 0.07	21.82 2.15 0.73 0.05
MgO 18.0 TiO_2 3.8 Cr_2O_3 0.0 MnO 0.0 Na ₂ 0 0.4 K ₂ O 7.9	8 18.87 0 2.66 0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46 0 2.76	3.63 0.00 0.08 0.45 8.12 0.07	3.04 0.01 0.13 0.49 8.28	3.90 0.02 0.07 0.44	2.13 0.75 0.09 0.47	21.07 2.12 0.29 0.07	2.15 0.73 0.05
$\begin{array}{cccc} 110_2 & & 3.2 \\ Cr_2O_3 & & 0.0 \\ MnO & & 0.0 \\ Na_2O & & 0.4 \\ K_2O & & 7.9 \\ C_2O & & 7.9 \\ C_2O & & 0.4 \\ \end{array}$	0 2.86 0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	0.00 0.08 0.45 8.12 0.07	0.01 0.13 0.49 8.28	0.02 0.07 0.44	0.75 0.09 0.47	0.29 0.07	0.73 0.05
$\begin{array}{c} C_{12}C_{3} & 0.0 \\ MnO & 0.0 \\ Na_{2}O & 0.4 \\ K_{2}O & 7.9 \\ C_{2}O & 0.0 \\ \end{array}$	0 0.00 9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	0.00 0.08 0.45 8.12 0.07	0.01 0.13 0.49 8.28	0.02	0.09 0.47	0.07	0.05
$\begin{array}{ccc} MHO & 0.0 \\ Na_20 & 0.4 \\ K_2O & 7.9 \\ C_2O & 7.9 \\ C_2O & 0.0 \\ C_2O & 0.$	9 0.10 1 0.43 5 8.83 8 0.05 4 2.46	0.08 0.45 8.12 0.07	0.13 0.49 8.28	0.07	0.09	0.07	0.05
K_2O 7.9	5 8.83 8 0.05 4 2.46	8.12 0.07	0.49 8.28	0.44	0.47		0.46
$K_2 U 7.9$	5 8.83 8 0.05 4 2.46	8.12 0.07	8.28		0.62	0.30	0.40
	4 2.46	0.07	0.00	8.09	9.03	9.03	9.85
CaU 0.0	4 2.46	1 70	0.09	0.06	0.02	0.02	0.00
BaO 5.2		4.70	3,35	4.96	0.86	0.87	0.84
F 0.8	0.76	0.70	0.73	0.61	0.56	0.56	0.54
O=F -0.3	4 -0.32	-0.29	-0.31	-0.26	-0.24	-0.24	-0.23
TOTAL 95.1	4 94.12	94.86	94.65	94.92	95.84	95.17	95.28
Si^{4+} 5.1	1 5.20	5.12	5.09	5.05	5.50	5.49	5.30
Al ³⁺ 2.8	9 2.80	2.88	2.91	2.95	2.50	2.51	2.70
8.0	0 8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al ³⁺ 0.1	6 0.20	0.07	0.17	0.08	0.18	0.23	0.08
Fe^{2+} 0.9	1.04	0.92	1.04	0.98	0.57	0.61	0.57
Mg^{2+} 4.0	4.21	4.27	4.21	4.20	4.70	4.65	4.86
Ti^{4+} 0.4	.3 0.30	0.41	0.34	0.44	0.23	0.23	0.24
Cr^{3+} 0.0	0.00	0.00	0.00	0.00	0.08	0.03	0.09
Mn^{2+} 0.0	0.01	0.01	0.02	0.01	0.01	0.01	0.01
5.4	-3 5.56	5.61	5.61	5.63	5.59	5.53	5.77
K ⁺ 1.5	1.69	1.56	1.58	1.56	1.75	1.77	1.87
Ca^{2+} 0.0	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Ba^{2+} 0.3	0.14	0.28	0.20	0.29	0.05	0.05	0.05
Na ⁺ 0.1	2 0.12	0.13	0.14	0.13	0.13	0.14	0.13
1.9	1.96	1.98	1.93	1.99	1.93	1.96	2.05
F 0.3	9 0.36	0.33	0.35	0.29	0.25	0.25	0.26
O ²⁻ 21.6	21.64	21.67	21.65	21.71	21.75	21.75	21.75
Cat sum 15.5	5 15.72	15.66	15.71	15.70	15.70	15.72	15.90
Mg/(Mg+Fe) 0.8 Fe/(Fe+Mg) 0.1	0.80 9 0.20	0.82 0.18	0.80 0.20	0.81 0.19	0.89 0.11	0.88	0.90 0.10

Table E.3: (Chemical composition of Yogo phlogopite) continued.

Sample	PH51	PH54	PH57	PH61	PH56	PH62	PH9A	PH9B
	Rim of m	negacryst	Rim of m	egacryst	Core of m	negacryst	Core of n	negacryst
5:0	26.18	22.50	22.87	34.60	38 26	38 30	37 10	37.20
SIO_2	16 60	33 .39 17 10	17.02	16.00	15.20	16 15	16 74	17.20
A_2O_3	6 5 1	7.10	17.02	10.90 9.09	15.64	10.15	5.62	5.63
reu Mao	10.51	10.04	18 66	0.00	21.06	72 04	20.02	20.28
Tio	2.84	3 87	3 75	3 35	21.90	22.04	20.93	20.28
Γ_{102}	2.04	0.05	0.04	0.00	0.64	0.37	0.06	0.22
$C_{12}O_{3}$ MnO	0.70	0.05	0.04	0.00	0.04	0.07	0.00	0.22
Nn 0	0.04	0.07	0.03	0.04	0.05	0.08	0.02	0.01
Na_20	0.30 8.04	0.45 8.00	0.47	0.40 Q /2	0.47	0.47	0.57	0.00
$K_2 O$	0.94	0.09	0.03	0.43	9.08	9.77	9.44	9.29
CaO BaO	2.60	4.85	4 70	2.87	0.03	1.08	1 10	1 30
DaU F	2.00	4.85	4.79	0.74	0.90	0.43	0.56	0.65
r O=F	0.00	-0.33	-0.30	-0.31	-0.21	-0.18	-0.24	-0.27
•	0.00	0.00	0.20					
TOTAL	95.39	95.22	95.33	95.62	95.07	95.62	94.97	95.02
Si ⁴⁺	5.35	5.04	5.08	5.16	5.50	5.49	5.42	5,38
Al ³⁺	2.65	2.96	2.92	2.84	2.50	2.51	2.58	2.62
	8 00	8 00	8 00	8 00	8.00	8.00	8.00	8.00
A1 ³⁺	0.26	0.06	0.09	0.12	0.19	0.22	0.27	0.31
Fe^{2+}	0.80	0.91	0.98	1.00	0.56	0.57	0.68	0.68
Mg ²⁺	4.32	4.26	4.17	4.21	4.71	4.71	4.51	4.37
Ti ⁴⁺	0.32	0.44	0.42	0.37	0.23	0.23	0.26	0.30
Cr ³⁺	0.09	0.01	0.00	0.00	0.07	0.04	0.01	0.03
Mn ²⁺	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
	5.54	5.63	5.58	5.59	5.58	5.56	5.46	5.38
K ⁺	1.69	1.55	1.55	1.60	1.78	1.79	1.74	1.71
Ca ²⁺	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00
Ba ²⁺	0.15	0.29	0.28	0.23	0.05	0.06	0.06	0.07
Na^+	0.10	0.13	0.14	0.14	0.13	0.13	0.16	0.14
	1.94	1.98	1.97	1.97	1.96	1.98	1.97	1.92
F ⁻	0.00	0.37	0.34	0.35	0.22	0.19	0.26	0.30
O ²⁻	22.00	21.63	21.66	21.65	21.78	21.81	21.74	21.70
Cat sum	15.74	15.67	15.64	15.68	15.73	15.76	15.70	15.61
Mg/(Mg+	0.84	0.82	0.81	0.81	0.89	0.89	0.87	0.87
Fe/(Fe+M	0.16	0.18	0.19	0.19	0.11	0.11	0.13	0.13

Table E.3: (Chemical composition of Yogo phlogopite) continued.

Sample	РН9С	PH9D	PH9G	PH9E	PH9F	PH10A	PH10B	PH10C
	Rin	of megacr	yst	Core of m	legacryst	Rim 3	Rim 2	Rim 1
5:0	31 15	36.77	31 78	37.03	38 10	34.00	38 14	37 33
$\Delta 1_{1}$	17 10	16 74	17.70	16.94	16.06	17.25	15.95	17 79
FeO	7 54	8 52	8 58	5 45	4 81	7.92	4 61	5 51
MgO	10.04	10 04	19.16	20.75	21.46	18 56	21.53	20.52
TiO	3 15	1 33	2.62	20.75	21.40	3 30	2 07	2 10
Γ_{1}	0.02	0.01	0.00	0.07	0.60	0.02	0.81	0.20
$M_{\rm PO}$	0.02	0.01	0.00	0.07	0.00	0.02	0.01	0.20
Na 0	0.10	0.20	0.15	0.04	0.05	0.08	0.00	0.62
Na ₂ 0	0.37	0.27	0.50	0.55	0.40	830	0.47	0.05
$K_2 O$	0.02	9.63	0.00	9.30	9.09	0.07	9.34	9.50
CaO D-O	0.03	0.32	0.09	0.07	1.02	0.07	1.03	1.25
БаО	3.71	0.77	2.32	1.17	1.03	4.54	0.42	0.30
F O F	0.79	0.98	0.70	0.46	0.49	0.03	0.43	0.39
U=F	-0.33	-0.41	-0.29	-0.19	-0.21	-0.27	-0.18	-0.16
TOTAL	95.12	95.14	94.96	94.39	95.09	95.26	94.45	95.19
Si ⁴⁺	5 14	5 3 2	5 17	5 30	5 50	5 10	5 52	5 30
Δ1 ³⁺	2.14	2.52	2.17	2.61	2 50	2 00	2 48	2.61
	2.00	2.08	2.0J 8.00	8.00	8.00	8.00	2.40 8.00	8.00
A1 ³⁺	0.15	0.22	0.00	0.30	0.00	0.15	0.24	0.42
E_{0}^{2+}	0.15	1.05	1.07	0.50	0.23	0.15	0.24	0.42
$M\alpha^{2+}$	0.94 1 2 1	1.05	1.07	4.51	4.61	0.99 A 15	4.64	4 41
1vig T: ⁴⁺	4.24	4.37	4.25	4.51	4.01	4.15	4.04	4.41
C_{r}^{3+}	0.35	0.15	0.29	0.20	0.24	0.38	0.23	0.23
Cr M- ²⁺	0.00	0.00	0.00	0.01	0.07	0.00	0.09	0.02
IVIN	0.01	0.02	0.02	0.00	0.01	0.01	5.52	5.00
1/+	5.54	5.59	2.03	5.44 1.77	5.51	5.55	3.33	3.32
K 0 ²⁺	1.68	1.84	1.05	1.77	1.78	1.59	1.72	1.72
Ca^{-1}	0.00	0.05	0.01	0.01	0.00	0.01	0.00	0.00
Ba ⁻	0.22	0.04	0.15	0.07	0.06	0.27	0.06	0.08
Na	0.11	0.08	0.14	0.16	0.13	0.14	0.13	0.18
¥7-	2.01	2.01	1.95	2.01	1.97	2.01	1.91	1.98
F ⁻	0.37	0.46	0.33	0.21	0.22	0.31	0.20	0.18
0 ²²	21.63	21.55	21.67	21.79	21.78	21.69	21.80	21.82
Cat sum	15.70	15.82	15.76	15.75	15.71	15.69	15.68	15.72
Mg/(Mg+Fe)	0.82	0.81	0.80	0 87	0 89	0.81	0.89	0.87
Fe/(Fe+Mg)	0.18	0.19	0.20	0.13	0.11	0.19	0.11	0.13

Table E.3: (Chemical composition of Yogo phlogopite) continued.

Sample	PH10D	PH10E	PH10F	PH10G	PH10H	PH11B	PH11C	PH11D
	Core of n	negacryst	Rim 2	Rim 1	Rim	Co	re of megac	ryst
SiO ₂	38.38	38.64	38.00	37.52	37.31	38.32	38.27	37.99
Al_2O_3	15.80	16.04	16.21	17.21	17.63	15.71	15.55	15.29
FeO	4.67	4.59	4.80	5.27	5.38	4.80	4.55	4.53
MgO	21.37	21.88	21.81	20.71	20.64	21.72	21.61	21.54
TiO ₂	1.84	1.88	1.98	2.06	2.15	2.15	2.14	2.09
Cr_2O_3	1.00	0.77	0.73	0.47	0.32	0.73	0.93	1.04
MnO	0.00	0.05	0.05	0.04	0.05	0.00	0.01	0.00
Na ₂ 0	0.48	0.45	0.52	0.58	0.62	0.46	0.46	0.43
K ₂ O	9.59	9.78	9.69	9.41	9.39	9.74	9.78	9.38
CaO	0.01	0.02	0.03	0.01	0.00	0.04	0.02	0.00
BaO	0.90	0.91	0.99	1.25	1.34	0.78	0.81	0.79
F	0.52	0.50	0.42	0.34	0.53	0.41	0.51	0.69
O=F	-0.22	-0.21	-0.18	-0.14	-0.22	-0.17	-0.21	-0.29
TOTAL	94.55	95.51	95.21	94.87	95.36	94.84	94.62	93.77
Si ⁴⁺	5 55	5 53	5 17	5 13	5 38	5 53	5 53	5 53
Δ1 ³⁺	2.55	2.55	2.47	2.43	2.38	2.55	2.55	2.33
	8.00	2.47 8.00	8.00	8.00	8.00	2.47	2.47	8.00
41 ³⁺	0.00	0.00	0.00	0.37	0.00	0.00	0.00	0.15
Fe^{2+}	0.24	0.24	0.22	0.54	0.57	0.20	0.10	0.15
$M\sigma^{2+}$	4.61	4 67	4 68	4 47	4 43	4 67	4 66	4 68
Ti ⁴⁺	0.20	0.20	0.21	0.22	0.23	0.23	0.23	0.23
Cr ³⁺	0.11	0.20	0.08	0.05	0.23	0.25	0.25	0.12
Mn ²⁺	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00
	5 48	5 52	5 56	5 39	5 36	5 56	5 55	5 58
К+	1 77	1 79	1 78	1 74	1 73	1 79	1.80	1 74
Ca^{2+}	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Ba ²⁺	0.05	0.05	0.06	0.07	0.08	0.04	0.05	0.05
Na ⁺	0.13	0.12	0.15	0.16	0.17	0.13	0.13	0.12
	1.95	1.96	1 99	1 97	1 98	1 97	1.98	1.91
F ⁻	0.24	0.23	0.19	0.16	0.24	0.19	0.23	0.32
0 ²⁻	21.76	21.77	21.81	21.84	21.76	21.81	21.77	21.68
Cat sum	15.67	15.72	15.77	15.72	15.70	15.73	15.71	15.64 Formula
Ma/(Ma+Fe)	0.80	0.80	0.80	0.87	0.87	0.80	0.80	0.80
Fe/(Fe+Mg)	0.11	0.11	0.89	0.13	0.13	0.11	0.11	0.11

Table E.3: (Chemical composition of Yogo phlogopite) continued.

Sample	P11D	PH11E	PH11F	PH11G
-	Mega	acryst	Mega	acryst
	Core	Rim	Core	Core
SiO ₂	34.21	34.23	37.77	38.46
Al_2O_3	17.14	17.17	15.86	15.64
FeO	7.02	6.96	4.63	4.54
MgO	19.41	19.45	21.58	21.69
TiO ₂	3.28	3.31	2.11	2.19
Cr_2O_3	0.22	0.29	0.54	0.72
MnO	0.04	0.04	0.04	0.06
Na ₂ 0	0.51	0.47	0.45	0.45
K ₂ O	8.26	8.27	9.60	9.66
CaO	0.09	0.07	0.02	0.00
BaO	4.13	4.13	0.97	0.83
F	0.70	0.71	0.49	0.38
O=F	-0.29	-0.30	-0.21	-0.16
TOTAL	94.99	95.10	94.05	94.61
C :4+	5 1 1	5 10	5 50	E
51 A 1 ³⁺	5.11	5.10	5.50	5.55
AI	2.89	2.90	2.50	2.45
A 13+	8.00	8.00	8.00	8.00
AI Σ_2^{2+}	0.13	0.12	0.22	0.21
ге М- ²⁺	0.88	0.87	0.50	0.55
NIG T: ^{4†}	4.32	4.32	4.08	4.07
11	0.37	0.37	0.23	0.24
Cr M^{2+}	0.03	0.03	0.06	0.08
Mn	0.01	0.01	0.00	0.01
v ⁺	5.61	5.6U	5.53	5.55
Λ	1.57	1.57	1.78	1.78
$Ca = D^{2+}$	0.01	0.01	0.00	0.00
Ba Nu ⁺	0.24	0.24	0.06	0.05
INa	0.15	0.14	0.13	0.13
F-	1.97	1.96	1.97	1.96
F 0 ²⁻	0.33	0.33	0.23	0.17
0-	21.67	21.67	21.78	21.83
Cat	15 71	15 69	15 70	15 70
Cat sum	13.71	10.08	13.72	13.72
Mg/(Mg+Fe)	0.83	0.83	0.89	0.89
Fe/(Fe+Mg)	0.17	0.17	0.11	0.11
= -: (2.24

Table E.3: (Chemical composition of Yogo phlogopite) continued.

APPENDIX F

EXPERIMENTAL CONDITIONS FOR ELECTRON MICROPROBE ANALYSES

Standard Package Name: PYROX1 Mineral Analyzed: Pyroxene Voltage: 15 Kv Current: 20 nA

Calibration Time (s) on STD	20	20	20	20	20	20	20	20	20	20
Analysis Time (s)	20	20	20	20	20	20	20	20	20	20
Negative Background	-700	-1500	-750	-700	-700	-600	-800	-450	-580	-600
Positive Background	700	1500	750	700	700	600	800	450	580	600
SPC Number	4	5	3	1	4	3	2	1	1	1
XTAL	TAP	TAP	PET	LIF	TAP	PET	TAP	Ш	LIF	LIF
Standard Name	Aegirine	Diopside	Diopside	Chromite	Diopside	Rutile	Grossularite	Aegirine	Pyroxm	Ni-Olivine
Standard Number	S246	S379	S379	S222	S379	S013	S007	S246	S245	S241
Element Analyzed	Na	Mg	Ca	Cr	Si	Ti	Ali	Fe	Mn	Ÿ

Standard Package Name: GPYR Mineral Analyzed: Pyroxene Voltage: 15 Kv Current: 20 nA

Calibration Time (s) on STD	20	20	20	20	20	20	20	20	20	20
Analysis Time (s)	20	20	20	20	20	20	20	20	07	20
Negative Background	-500	-1500	-750	-700	-700	-800	-600	-700	-580	-600
Positive Background	500	1500	750	700	700	800	650	700	580	600
SPC Number	1	2	ω	4	1	4	3	4	1	1
XTAL	LIF	TAP	PET	TAP	LLF	ТАР	PET	TAP	LIF	LIF
Standard Name										
Standard Number										
Element Analyzed	Fe	Mg	Ca	Na	Cr	AI	Ti	Si	Mn	Ň

Standard Package Name: SPINEL Mineral Analyzed: Spinel (pleonaste, chromite, magnetite) Voltage: 15 Kv Current: 20 nA

Calibration Time (s) on STD	20	20	20	20	20	20	20	20	20	20
Analysis Time (s)	20	20	20	20	20	20	20	20	20	20
Negative Background	-450	-1500	-580	-600	-700	-700	-600	-750	-700	-800
Positive Background	450	1500	580	600	700	700	600	750	700	800
SPC Number	1	7	1	3	1	4	1	3	1	2
XTAL	LIF	TAP	ГІГ	PET	LIF	TAP	LIF	PET	LIF	TAP
Standard Name	Fayalite	Forsterite	Pyroxm	Rutile	Chromite	Diopside	Ni-Olivine	Diopside	Sphalerite	Grossularite
Standard Number	T104	S022	S245	S013	S222	S379	S241	S379	S141	S007
Element Analyzed	Fe	Mg	Mn	Ï	C	Si	Ÿ	Ca	Zn	AI

Standard Package Name: GSPIN (February 1993), SPIN (May 1993) Mineral Analyzed: Spinel (pleonaste, chromite, magnetite) Voltage: 15 Kv Current: 20 nA

Calibration Time (s) on STD 20 20 20 20 20 20 20 20 20 20 20 Analysis Time ં 20 20 20 20 20 20 20 20 20 20 20 Background Negative -1400 -1500 -700 -600 -580 -800 -600 -750 -550 -700 -700 Background Positive 1500 700 700 600 580 800 600 750 650 700 700 Number SPC 2 e ---4 2 e 4 2 \mathfrak{C} _ XTAL TAP TAP TAP LIF LIF PET LIF LIF PET LIF LIF Standard Name Spessartine Ni-Olivine Sphalerite Fayalite Chromite Chromite Fayalite Diopside Rutile Spinel > Standard Number **T**104 S440 S441 S442 S241 S439 **S**309 T104 S441 S431 S141 Element Analyzed Mg Mh Бе S Ë P ï S Zn > $\overline{\mathbf{S}}$

Standard Package Name: SAPH Mineral Analyzed: Corundum (sapphire) Voltage: 15 Kv Current: 40 nA

Calibration Time (s) on STD	20	20	50	5	20	20	20
Analysis Time (s)	300	300	300	5	300	300	300
Negative Background	-1400	-600	-700	-800	-580	-650	-1500
Positive Background	700	650	700	800	580	650	1500
SPC Number	1	2	3	4	1	3	4
XTAL	LIF	PET	LIF	TAP	LIF	LIF	TAP
Standard Name	Fayalite	Rutile	Chromite	Synthetic Corundum	Rhodonite	Λ	Diopside
Standard Number	T104	S442	S382	S432	S 459	S 309	S439
ed H							

Standard Package Name: GARNET Mineral Analyzed: Garnet Voltage: 15 Kv Current: 20 nA

Calibration Time (s) on STD	20	20	20	20	20	20	20	20	20
Analysis Time (s)	20	20	20	20	20	20	20	20	20
Negative Background	002-	-750	008-	002-	-580	-1500	-1400	-600	002-
Positive Background	700	750	800	700	580	1500	700	650	700
SPC Number	2	3	2	4	1	2	1	3	1
XTAL	TAP	PET	d YL	d YL	LIF	TAP	ШŢ	PET	LIF
Standard Name	Albite	Grossularite	Grossularite	Grossularite	Rhodonite	Diopside	Fayalite	Rutile	Chromite
Standard Number	S430	S 007	S007	S007	S459	S439	T104	S442	S441
Element Analyzed	Na	Са	AI	Si	Mn	Mg	Fe (Fe ²⁺)	Ë	Ċ

Mineral Analyzed: Zeolite (analcime) Voltage: 15 Kv Current: 10 nA

ime										
Calibration 7 (s) on ST	20	20	20	20	20	20	20	20	20	20
Analysis Time (s)	20	20	20	20	20	20	20	20	20	20
Negative Background	-500	-700	-550	-800	-580	-1500	-750	-700	-650	-650
Positive Background	500	700	550	800	580	1500	750	700	650	650
SPC Number	1	2	з	4	1	2	3	4	2	3
XTAL	LIF	TAP	PET	TAP	LIF	TAP	PET	TAP	TAP	PET
Standard Name	Fayalite	Albite	Orthoclase	Anorthite	Spessartine	Diopside	Anorthite	Orthoclase	SrTiO ₃	Barite
Standard Number	T104	S 430	S438	T101	S440	S439	T101	S438	S446	S448
Element Analyzed	Fe (Fe ²⁺)	Na	K	AI	Mn	Mg	Са	Si	Sr	Ba