

PETROLOGY OF THE GOLDEN CLUSTER LAMPROPHYRIES IN SOUTHEASTERN BRITISH COLUMBIA (82N)

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INTRODUCTION

Lamprophyre diatremes and dikes of probable Paleozoic age occur in three areas of eastern British Columbia. These are: the Ospika River diatreme in the north (Pell, 1986, 1987a, b), a cluster of diatremes and dikes near Golden (Ijewliw, 1986, 1987; Pell, 1986, 1987a, b; Ijewliw and Schulze, 1988) and another cluster in the Cranbrook - Bull River area in the south (Leech, 1958, 1964, 1965, 1979; Grieve, 1981, 1982; Ijewliw, 1986, 1987; Pell, 1986, 1987a, b; Hall *et al.*, 1989; Hall 1991; Helmstaedt *et al.*, 1988). These three groups of diatremes are aligned in a north-northwest belt northeast of the Rocky Mountain Trench within the Western and Main ranges of the Rocky Mountain fold and thrust belt. They vary, however, with respect to their rock types, stratigraphic position, time of emplacement and structural setting.

The northern Ospika pipe and the central Golden cluster are lamprophyres of the ultramafic, calcalkaline or alkaline branches, whereas the diatremes of the southern Cranbrook - Bull River cluster, with the exception of the Cross kimberlite, are more difficult to classify due to severe alteration. Some of them resemble limburgites or olivine melilitites (Grieve, 1981; Ijewliw, 1986, 1987; Pell, 1986, 1987b; Hall, 1990).

Since the 1970s, diatreme facies rocks in eastern British Columbia have generated some exploration interest due to their presumed similarity to kimberlites, possible carriers of diamonds (Pell, 1986). In this note the chemical composition of clinopyroxenes and spinels in two of the Golden cluster lamprophyres, HP and Mons Creek pipes are examined in order to better understand the igneous processes.

GEOLOGICAL SETTING

The Golden cluster lamprophyres extend over a curvilinear distance of about 55 kilometres along a southeasterly trend. They occur at distances ranging from 40 to 90 kilometres north of the town of Golden, British Columbia (Table 1-4-1) and are located on NTS map 82N. The lamprophyres lie within a single structural unit in Cambro-Ordovician carbonate strata, west of the west-dipping Mons Creek fault. Its continuity is unbroken by any major faults. Each location comprises a diatreme or breccia phase(s) with associated or crosscutting dikes. The degree of preservation varies from the relatively well preserved HP pipe and the relatively fresh Mons Creek float samples; to the moderately preserved Bush River site, which retains both primary

minerals and clearly discernible pseudo-norphs of altered minerals; to the severely altered rocks at Valenciennes River and the tuffitic rocks on Lens Mountain in which primary textures and mineralogy are no longer discernible.

Classification of the Golden cluster diatremes (Table 1-4-2) is based primarily on the extensive work of Rock (1977, 1984, 1986, 1987, 1989) and the IJGS recommendations (Streckeisen, 1979) regarding lamprophyre nomenclature. Based on a survey of the lamprophyre literature, Rock (1987) prepared a scheme for lamprophyre definition, distinction and nomenclature. The definition stated that essential mineral phases should include amphiboles, biotites, phlogopites and other volatile-rich minerals such as halides, carbonates, sulphates and zeolites, in addition to feldspars and quartz with coexisting magnesium-rich mafic minerals, olivine and clinopyroxene. Neither feldspars nor quartz occur as phenocrysts and olivine does not occur in the groundmass (Rock, 1977, 1984, 1987).

MINERAL CHEMISTRY

The chemical composition of fresh, cognate minerals occurring in the Golden cluster lamprophyres was determined in order to assist in lamprophyre classification as, to a limited extent, a given rock type contains minerals within a limited compositional range. Additionally, mineral compositions may elucidate the igneous processes occurring during the evolution of a given rock. Mineral chemical data from the HP and Mons Creek pipe clinopyroxenes and spinels are characteristic for each pipe.

Mineral chemical compositions were determined using an ARL SEMQ microprobe at Queen's University. Structural formulae for clinopyroxenes were calculated based on six

TABLE 1-4-1
LOCATIONS OF THE GOLDEN CLUSTER LAMPROPHYRES

Pipe	Latitude and Longitude	Elevation
Bush River	52°05'00"N & 117°23'00"W	2,95 m (7200 ft)
Lens Mountain	51°54'15"N & 117°07'30"W	2,794 m (9200 ft)
Mons Creek	51°49'30"N & 117°00'30"W	2,225 m (7300 ft)
Valenciennes River	51°47'00"N & 116°58'30"W	2,591 m (8500 ft)
HP Pipe	51°41'30"N & 116°57'15"W	2,195 m (7200 ft)

TABLE 1-4-2
GOLDEN CLUSTER LAMPROPHYRE CLASSIFICATION

Location	Name	Branch
Bush River	olivine kersantite	Calcalkaline
Mons Creek	biotite camptonite	Alkaline
Valenciennes River	camptonite	Alkaline
HP Pipe	aillikite	Ultramafic

oxygens, assuming a $(W)_{1-p}(X,Y)_1 + pZ_2O_6$ stoichiometry, where: $W = Ca, Na, K$; $X = Mg, Fe^{2+}, Mn$; $Y = Fe^{3+}, Al, VI, Ti, Cr$; $Z = Si, Al-IV$ (Deer *et al.*, 1978). Using the methods of Deer *et al.* (1966), cations were normalized to four and, using either oxygen deficiency or charge balance considerations, the Fe^{3+} cation component was calculated. Structural formulae for spinels were calculated based on four oxygens, assuming an XY_2O_4 stoichiometry, where: $X = Mg, Fe^{2+}, Mn$; $Y = Cr, Al, Fe^{3+}, Ti$ (Deer *et al.*, 1962). Cations were normalized to three and the Fe^{3+} cation component was calculated as for the clinopyroxenes.

HP PIPE HOMOGENEOUS CLINOPYROXENES

Contrary to expectations, the HP pipe clinopyroxene chemical compositions are independent of whether they are from the breccia or dike phases and are also independent of size, that is, megacryst, macrocryst or phenocryst sizes. Consequently, all of the chemical data are grouped together. Seventy-five clinopyroxene grains were analysed. A majority, 87 per cent (65 out of 75 grains) of the HP pipe clinopyroxenes are not zoned. Microprobe testing confirmed that the grains are homogeneous where optical zoning is not seen.

In hand sample, the HP pipe clinopyroxenes can be easily divided, on the basis of colour, into the bright green diopsides and the black diopsides and salites. This distinction is reflected in the chemical analyses; the green clinopyroxenes are chrome diopsides with an average of 1.0 weight per cent Cr_2O_3 and the black diopsides and salites are virtually devoid of chromium.

Thin-section colour is also correlated with chemical composition. Pyroxenes with green pleochroism have the highest amounts of FeO (11.3–15.7 wt.%), those with pink pleochroism have the highest TiO_2 contents (1.9–2.8 wt.%) and those with pink and green pleochroism are high in both iron and titanium. Nonpleochroic, clear or white grains are highest in MgO (12.3–17.0 wt.%). The highest aluminum values are in the 13.11 to 14.52 weight per cent Al_2O_3 range and the highest sodium values range from 2.02 to 2.33 weight per cent Na_2O .

The HP pipe has three groups of clinopyroxenes. They are distinct with respect to Mg , Fe , $Mg\#$ [$Mg\# = Mg/(Mg + Fe(\text{total}) + Mn)$] and chrome contents, but there is overlap in the other major elements. The high- $Mg\#$ diopside group [$Mg\# > 0.90$] is chrome rich, green in hand sample and white in thin section. The intermediate- $Mg\#$ diopside group, [$Mg\# = 0.78 - 0.88$] is chrome poor, black-brown in hand sample and pale tan or green pleochroic in thin-section. Both the high and intermediate- $Mg\#$ clinopyroxene groups have a negative correlation between $Mg\#$ and Ti cations (Figure 1-4-1). The low- $Mg\#$ salite group, [$Mg\# = 0.45 - 0.68$] is also chrome poor, black-brown in hand sample and green in thin-section. This group's values have too much scatter to unequivocally establish a trend (Figure 1-4-1).

Lamprophyre clinopyroxenes (excluding those of kimberlites) tend to be in the diopside, salite or augite fields (Rock, 1987). Comparing the HP pipe clinopyroxene compositions with those of different lamprophyre branches as well as anhydrous, ultramafic rocks given by Rock (1987)

and Bergman (1987) reveals that the chrome diopsides of the high- $Mg\#$ group correspond closely to those from alpine-type peridotites and are intermediate in composition between lamproite and kimberlite clinopyroxenes (Bergman, 1987; Rock, 1987). They also correspond to the ultramafic lamprophyre clinopyroxenes of Rock (1987) within one or sometimes two standard deviations. The intermediate- $Mg\#$ group, the chrome-poor diopsides, corresponds to the ultramafic lamprophyre clinopyroxenes of Rock (1987). The low- $Mg\#$ group, the salites, corresponds to the alkaline and the ultramafic lamprophyre clinopyroxenes within one or two standard deviations (Rock, 1987), as well as to clinopyroxenes from alkaline olivine basalts and alkaline intrusives (Bergman, 1987).

Thus, it appears that at least the intermediate- $Mg\#$ clinopyroxenes of the HP pipe support the designation of this rock within the ultramafic lamprophyre branch and that the other clinopyroxene groups have elemental values in common with other undersaturated alkaline rocks and lamprophyre branches. The chemical discontinuities and distinct trends make it unlikely that the three clinopyroxene groups are part of one system. The origins of the three groups and their relationship to each other are discussed in the following section.

Chrome diopsides are commonly considered to have originated from disaggregated peridotites (Brooks and Printzlau, 1978; Wass, 1979). However, the HP pipe high- $Mg\#$ chrome diopsides are chemically distinct from clinopyroxene xenoliths and xenocrysts occurring in lamproites, kimberlites, alkali olivine basalts and lamprophyres in the amounts of silica, aluminum, iron and calcium (Bergman, 1987). The HP high- $Mg\#$ chrome diopsides range in size up to 2 to 3 centimetres in diameter and are significantly larger than average lherzolite clinopyroxenes which are less than 30 millimetres in diameter (Eggler *et al.*, 1979). The HP pipe chrome diopsides are unlikely to have derived from disaggregated peridotites as they differ in chemical composition and are much coarser grained. They are also thought to be cognate to the HP pipe system(s) because the rims of the zoned grains are of a similar composition. The small variations in $Mg\#$ and the other major

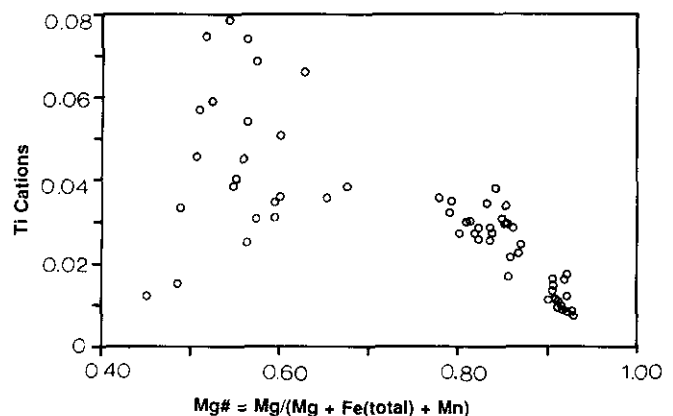


Figure 1-4-1. HP pipe homogeneous clinopyroxenes. $Mg\#$ versus Ti cations. The high and intermediate $Mg\#$ groups have negative correlations with titanium contents.

elements measured, and the clear correlations, suggest that a small degree of fractionation occurred in this group.

The intermediate-Mg# chrome-free diopside group corresponds in composition to those from ultramafic lamprophyres (Rock, 1987) and is considered to be cognate to the HP pipe system. The wide variation and distinct negative correlations between Mg# and Ti cations (Figure 1-4-1) indicate that this clinopyroxene group may have crystallized in a fractionating liquid which was becoming progressively enriched in iron, aluminum and titanium. A similar pattern exists among chrome-poor megacrysts in the Colorado-Wyoming kimberlites and was also attributed to fractionation (Eggler *et al.*, 1979). Gurney *et al.* (1979) similarly noted a linear trend of increasing TiO₂ with increasing FeO from the Monastery kimberlite pipe in South Africa. Malaita alnoite (ultramafic lamprophyre) contains subcalcic diopsides and augites with fractionation trends similar to this intermediate-Mg# HP group and these cognate clinopyroxenes are chemically distinct from xenolithic lherzolite clinopyroxenes found in the same pipe (Nixon and Boyd, 1979). Therefore, it is suggested that fractional crystallization is the dominant process controlling the trends in the intermediate-Mg# clinopyroxene group.

The low-Mg# salite group has the most variability in both Mg# and component elements and no clear negative correlation with Ti cations (Figure 1-4-1). Salites or green clinopyroxenes of slightly varying chemical compositions are found in a variety of alkaline hydrous and nonhydrous rocks. Explanations for their occurrence include that they may be xenocrysts from other magma systems (Pe-Piper, 1984; O'Brien *et al.*, 1988; Pe-Piper and Jansa, 1988), or xenocrysts from disaggregated xenoliths (Barton and van Bergen, 1981).

When zoned, the HP salites have irregular, rounded and lobate green cores with narrow, subhedral, white overgrowths and correspondingly sharp compositional changes from a high-iron core to a low-iron rim. There is a distinct gap in the iron and magnesium contents between the intermediate and low-Mg# (gap is Mg# 0.68–0.78) clinopyroxene groups. Average weight per cents of the other major elements are distinct beyond one standard deviation. Reverse zoning and compositional gaps suggest that the green salites are most likely accidental inclusions from another system encountered en route by the HP intrusion.

In summary, the three distinct clinopyroxene populations in the HP pipe comprise: the high-Mg#, cognate chrome diopsides fractionating from a new primitive melt; intermediate-Mg#, chrome-free diopsides in a fractionating system; and, low-Mg#, xenocrystic salites.

HP PIPE ZONED CLINOPYROXENES

The cores of the zoned grains correspond in composition to the low and intermediate-Mg# unzoned clinopyroxenes, whereas the rims correspond to the intermediate and high-Mg# unzoned grains (compare Figure 1-4-2 to Figure 1-4-1). The gap in Mg# between the low and intermediate-Mg# zoned cores is similar to the gap in the unzoned grains. The gap between the high and intermediate-Mg# groups is not as evident in the rims. The zoned clinopyroxenes are thus a particular subset of the three groups of homogeneous

clinopyroxenes and can be ascribed to the same lamprophyre branches as the corresponding Mg# indicates. There is a preponderance of clinopyroxene zones with the intermediate-Mg# group which also supports the designation of the HP pipe within the ultramafic lamprophyre branch.

The zoned grains do not differ texturally from the homogeneous clinopyroxenes. They vary in size and occur both in the breccia and dike phases but are slightly more prevalent in the dikes. Only 13 per cent (10 out of the 75) of the HP pipe clinopyroxenes examined show optical and chemical zoning. These grains have green or pink cores and white rims. Only two zones, core and rim, are apparent except for a single grain where four zones are noted.

The zoned clinopyroxenes are characterized by iron-rich cores and very narrow magnesium-rich rims. Figure 1-4-2 shows that the cores which are particularly rich in titanium also have rims which are relatively enriched in these elements. Similarly, the cores which are relatively poor in magnesium also have relatively magnesium-poor rims. The most magnesium-rich and titanium-poor rims are similar to the high-Mg# chrome diopside group (Figure 1-4-2). Therefore, it is postulated that a new magma batch, in equilibrium with the high-Mg# clinopyroxene group, entered the system, reacted with the previously formed diopsides and xenocrystic salites and formed rims of intermediate composition. It is suggested that the new magma pulse may have triggered the eruption of the HP system.

Only the high-Mg#, homogeneous clinopyroxene group has appreciable chrome. The cores of the zoned grains are all chrome free, whereas some of the rims are enriched in chrome. This corroborates the idea of an influx of primitive magma because chrome cannot remain residual in a system during fractional crystallization.

MONS CREEK CLINOPYROXENES

Thirteen clinopyroxenes were analysed on the microprobe: nine complexly zoned phenocrysts and simply zoned groundmass grains and four homogeneous groundmass

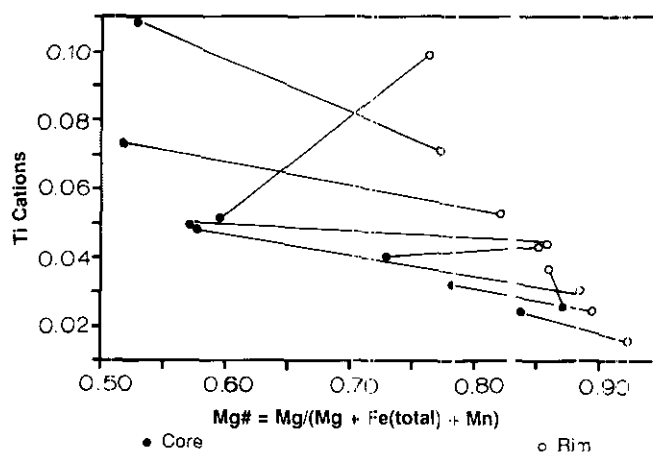


Figure 1-4-2. HP pipe zoned clinopyroxenes, Mg# versus Ti cations. The rims are magnesium and titanium enriched.

grains. Zoning traverses were made at 30 to 100-micron intervals and resulted in 2 to 22 spots being analysed per grain, depending on the complexity of the optical zoning. Despite such detailed examination, chemical distinctions are only noted on the scale of core, mantle and rim variations. The composition of the groundmass grains spans the range of compositions of the individual zones of the zoned clinopyroxenes.

Whereas the Mons Creek clinopyroxenes are more complexly zoned than those from the HP pipe, there are some similarities. If chrome is present in the Mons Creek clinopyroxenes, it commonly occurs in the rims or mantles (0.83–1.20 wt.% Cr₂O₃). This is similar to the HP pipe chrome diopsides. The cores of the larger zoned grains and the unzoned groundmass grains are relatively chrome poor (<0.40 wt.% Cr₂O₃) and some grains are entirely chrome free. Colour in thin section is related to chemical composition in that the green portions are particularly iron rich (8.23–12.19 wt.% FeO) but less so than the iron-rich grains from the HP pipe. The brown portions are particularly titanium rich (1.93–2.77 wt.% TiO₂), similar to HP pipe values, and the highest values occur in the mantles and rims. The highest magnesium values are in the 15.13 to 16.58 weight per cent MgO range, similar to HP pipe values, and occur in the grain mantles and cores. The highest aluminum values range from 9.30 to 10.43 weight per cent Al₂O₃ which is lower than in the HP pipe, and the highest sodium contents are 0.91 to 1.10 weight per cent Na₂O which is also lower than for the HP pipe. There are oscillations in all elements.

The Mons Creek clinopyroxenes have a complexity of zoning variations. At least six patterns can be discerned and two of these, Patterns 3 and 5 will be examined in this paper. Pattern 3 is a combination of simple reverse zoning, that is, increasing magnesium and chrome from core to mantle, followed by simple normal zoning, increasing iron, aluminum and titanium from mantle to rim (Figure 1-4-3). Simple reverse zoning is attributed to the entrainment of xenocrysts or previously crystallized grains in a more primitive melt, whereas, simple normal zoning is considered to be the result of fractionation. This pattern of zoning directions could occur in a grain entrained in a more primitive melt with subsequent overgrowths of more fractionated material. Pattern 5 is a combination of simple normal zoning, from core to mantle, followed by anomalous normal zoning, increasing iron but decreasing aluminum and titanium from mantle to rim (Figure 1-4-4). Anomalous normal zoning occurs as the last stages in grains exhibiting complex zoning patterns. The source of this outer material may be the melting of iron-rich, titanium, aluminum-poor xenocrysts or their entraining material possibly as a result of a cognate grain with fractionated overgrowths coming into contact with a xenocrystic melt.

In summary, these variations in the zoning directions and patterns indicate a relatively prolonged period of crystal interaction with fractionated, primitive and xenocrystic melts. It is postulated that there were at least two pulses of melting. Following the first melting episode, crystallization of clinopyroxenes occurred with later overgrowths of fractionated material (normal zoning). A second melting epi-

sode is inferred from the primitive overgrowths on previously crystallized grains (reverse zoning). Fractionation of the second melt also occurred as evidenced by the normally zoned groundmass grains. Both melts produced clinopyroxenes of similar composition and similar fractionation patterns. Xenocrysts, distinct in chemical composition (Fe-rich, Al and Ti-poor) from the cognate grains, were entrained and subsequently rimmed with fractionated or primitive melt. The xenocrysts or their enclosing melt also interacted with the cognate grains, rimming them in turn (anomalous zoning). Such complex interactions among melt episodes and xenocrystic material suggest a prolonged time period for all the events to have transpired and sufficient turbulence or convection to have allowed the mixing.

The compositions of the Mons Creek clinopyroxenes range from the HP intermediate-Mg# group to midway towards the low-Mg# group. The outstanding difference

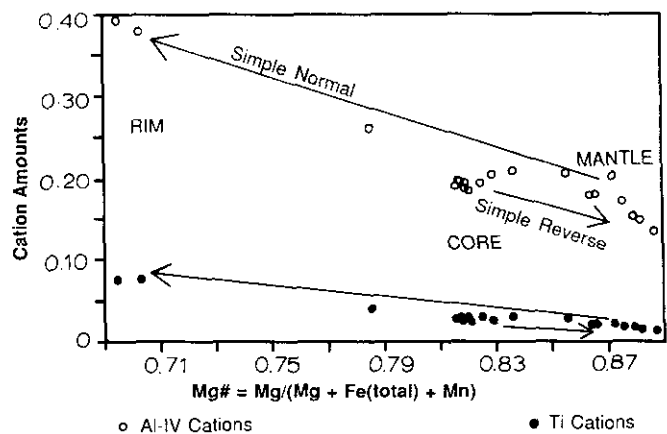


Figure 1-4-3. Mons Creek complexly zoned clinopyroxenes. Pattern 3, simple reverse zoning (with Mg# up, Al-IV, Ti down) followed by simple normal zoning (with Mg# down, Al-IV, Ti up) from core through mantle to rim.

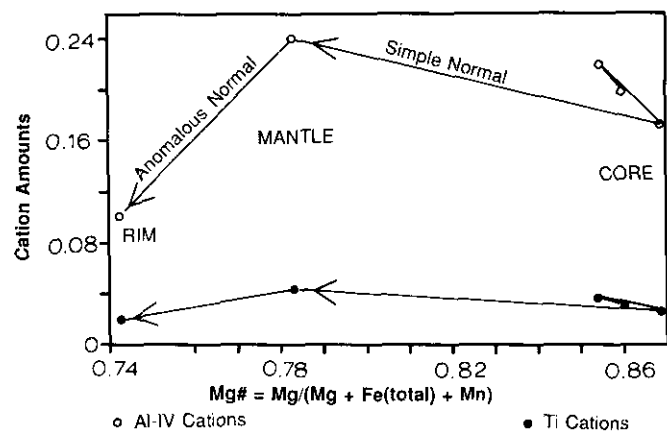


Figure 1-4-4. Mons Creek complexly zoned clinopyroxenes. Pattern 5, simple normal zoning (with Mg# down, Al-IV, Ti up) followed by anomalous normal zoning (with Mg# down, Al-IV, Ti down) from core through mantle to rim.

between the HP and Mons Creek pipes is the degree of zoning. At the HP pipe, the zoning is simple with very narrow rims upon rounded and resorbed cores. These rims are the reaction product of the xenocrystic or fractionated cores and primitive rimming material. At Mons Creek, on the other hand, the zoning is multiple, and sometimes oscillatory. It is the product of repetitive interaction among xenocrystic, fractionated and primitive melts. This suggests that the HP pipe was emplaced very shortly after the primitive magma pulse, whereas the Mons Creek diatreme had a comparatively much longer residence time prior to ascent to the surface.

In both the Mons Creek and the HP pipes, the lowest Mg# green clinopyroxene groups are considered to be xenocrysts. They have been rimmed by the cognate melt, but only at Mons Creek has a melt similar in composition to the xenocrysts also rimmed the cognate grains.

GOLDEN CLUSTER SPINELS

Twenty-seven grains, nine phenocrysts and eighteen groundmass spinels from the HP pipe were analysed. Eight phenocryst spinels were checked for zoning and found to be homogeneous except for one grain with a magnesium-rich core and iron-rich rim. Breccia and dike-phase spinels are neither optically nor chemically distinct from each other.

The HP spinels plot within the magnesiochromite quarter at the base of the spinel prism. They show some variation in chrome and aluminum and very little variation in iron and magnesium (Figure 1-4-5). Chrome contents range from 44.20 to 50.60 weight per cent Cr_2O_3 , and titanium ranges from 0.57 to 1.13 weight per cent TiO_2 .

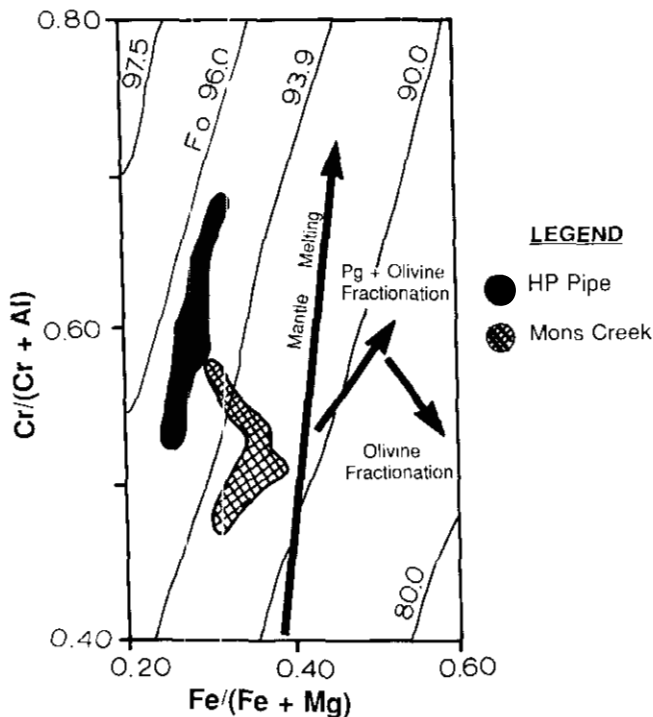


Figure 1-4-5. Comparison of HP and Mons Creek spinel compositional trends to the interpretations of Dick and Bullen (1984) for anhydrous mafic rocks.

Ten spinels, six phenocryst and four groundmass grains from Mons Creek were analysed and examined for zoning from core to rim. There are no consistent zoning patterns, although one grain has a high-chrome, low-aluminum core and another has a high-magnesium, low-iron core.

Mons Creek spinels fall predominantly within the magnesiochromite quarter at the base of the spinel prism, are homogeneous, except for two values, and show a modest variation in chrome and aluminum and in the iron/magnesium component (Figure 1-4-5). A bimodal distribution of Cr# is seen: a high-Cr# group (>0.54) has a negative correlation with $\text{Fe}^{2+}\#$, and a low-Cr# group (<0.52) has a positive correlation with $\text{Fe}^{2+}\#$. Chrome ranges from 36.52 to 45.12 weight per cent Cr_2O_3 , with one sample measuring at 53.24 weight per cent Cr_2O_3 . Titanium does not exceed 0.91 weight per cent TiO_2 .

In the HP and Mons Creek pipes, the spinels are optically similar but have distinct chemical trends characteristic of each pipe. They are disseminated throughout the groundmass and are not intergrown with, or included within, other minerals.

The Golden cluster magnesiochromites differ from typical, ultramafic lamprophyre titanomagnetites (Rock, 1986; Bergman, 1987). However, they are closer in composition to the subset of ceylonites, chromites or magnesiochromites from specific, ultramafic lamprophyres, especially aillikites (Mitchell, 1983; Rock, 1986). The magnesiochromite spinels from lamprophyres of extreme composition, kimberlites and lamproites, also have some similarities to the Golden cluster magnesiochromites (Mitchell, 1985). Additionally, the Golden magnesiochromite values and trends resemble those from the nonhydrated, ultramafic, alpine-type peridotites (Irvine, 1967; Bergman, 1987). Either they crystallized from a hydrated, peridotitic mantle melt or are merely xenocrysts from disaggregated peridotites.

For most spinels, there is a small increase in $\text{Fe}^{2+}\#$ accompanied by a larger increase in Cr#. A combination of Irvine's (1965) thermodynamic treatment and data from Jackson (1969), using the base of the spinel prism, shows some possible interpretations of these trends (Figure 1-4-5). Spinel chemical compositions in equilibrium with olivine forsterite content isopleths are shown. Proposed mechanisms are partial mantle melting characterized by a significant variation in Cr# and very little variation in $\text{Fe}^{2+}\#$, (very steep slope), plagioclase plus olivine and fractionation (shallower slope), or olivine fractionation alone (shallow slope and an inverse relationship between Cr# and $\text{Fe}^{2+}\#$).

High-chromium spinels are not usually found with high-iron, high-aluminum silicates but rather with high-magnesium silicates such as olivine (Dick and Bullen, 1984). When olivine and spinel fractionate, there is a decrease of magnesium and chrome in the melt and liquidus phases, resulting in a decrease in Mg# (increase in $\text{Fe}^{2+}\#$) and Cr# of the spinels. When plagioclase also fractionates, aluminum decreases in the melt and Cr# of the spinels goes up (Dick and Bullen, 1984). Allan *et al.* (1988) also concluded that coprecipitation of olivine and plagioclase causes the magma to increase in Fe^{2+} and decrease in aluminum in mid-ocean ridge basalts of the Lamont seamount chain, and thus the coprecipitating spinels will tend towards higher Cr#

and $\text{Fe}^{2+\#}$. Haggerty (1979), on the other hand, concluded that higher pressure spinels in spinel lherzolites are more aluminous because chrome is preferentially incorporated into clinopyroxene and at lower pressure the spinels are more chromiferous because aluminum is incorporated into plagioclase. This implies some coprecipitation of spinels and clinopyroxenes.

If hydrous rocks, such as lamprophyres, allowed the coprecipitation of spinels and clinopyroxenes, the iron enrichment and chrome depletion would be similar to the olivine fractionation pattern as the magnesium-iron partitioning is similar in both olivines and clinopyroxenes. Chrome in the melt would also be sharply depleted by being incorporated into both the clinopyroxenes and spinels. Therefore an olivine-plus-spinel fractionating pattern might be indistinguishable from a clinopyroxene-plus-spinel fractionating pattern in a hydrous melt.

The compositional ranges of the Golden magnesiochromites are not extensive. Nevertheless, the chemical trends exhibited by each pipe are characteristic and indicative of various igneous processes. The slopes and directions of $\text{Cr}\#$ versus $\text{Fe}^{2+\#}$ plots among the magnesiochromites imply a number of different processes. The HP magnesiochromite trend is ambiguous. The steep slope, moderate variation in $\text{Cr}\#$ and increasing forsterite content of equilibrium olivines lies between the slope indicating increased partial melting of the mantle and the slope indicating fractionation (Figure 1-4-5). The variation in HP clinopyroxene chemistry suggests that a differentiating magma was incorporated into a more primitive batch, perhaps generated by an increase in mantle partial melting, just prior to ascent. Thus, the increase in the $\text{Cr}\#$ of the HP magnesiochromites might simply reflect an increase in partial melting of the mantle.

The HP clinopyroxene trends also suggest fractionation, but this is not clearly evident for the spinel trend, as shown in Figure 1-4-5. To test for evidence of fractionation among the HP spinels, it is necessary to look at other chemical parameters. If increasing $\text{Cr}\#$ is due to increased partial melting, then there should be no correlation with $\text{Ti}\#$ [$(\text{Ti}/\text{Ti}+\text{Cr}+\text{Al})$] or $\text{Fe}^{3+\#}$ [$(\text{Fe}^{3+}/\text{Fe}^{3+}+\text{Cr}+\text{Al})$]. Titanium contents might even be expected to decrease with increased mantle partial melting. Additionally, as increasing $\text{Fe}^{3+\#}$ implies increased oxygen fugacity and/or lower confining pressures, increased partial melting should yield uniform $\text{Fe}^{3+\#}$. But, Figures 1-4-6 and 1-4-7 and Table 1-4-3 show a clear positive correlation between $\text{Cr}\#$ and $\text{Ti}\#$ and a modest positive correlation between $\text{Cr}\#$ and $\text{Fe}^{3+\#}$. Increasing both $\text{Ti}\#$ and $\text{Fe}^{3+\#}$ is consistent with fractionation. Titanium is an incompatible element and is incorporated into minerals during the latter stages of crystallization. The amount of Fe^{3+} also increases as crystallization proceeds. Therefore, the increases in $\text{Ti}\#$ and Fe^{3+} support the fractionation hypothesis among the HP magnesiochromites.

The Mons Creek magnesiochromite trend is bimodal (Figure 1-4-5). The lower $\text{Cr}\#$ lobe has both increasing $\text{Fe}^{2+\#}$ and $\text{Cr}\#$ which is consistent with an interpretation of an olivine-plus-plagioclase fractionation. The higher $\text{Cr}\#$ lobe shows decreasing $\text{Cr}\#$ with increasing $\text{Fe}^{2+\#}$ consistent with olivine fractionation. Plagioclase is found in the

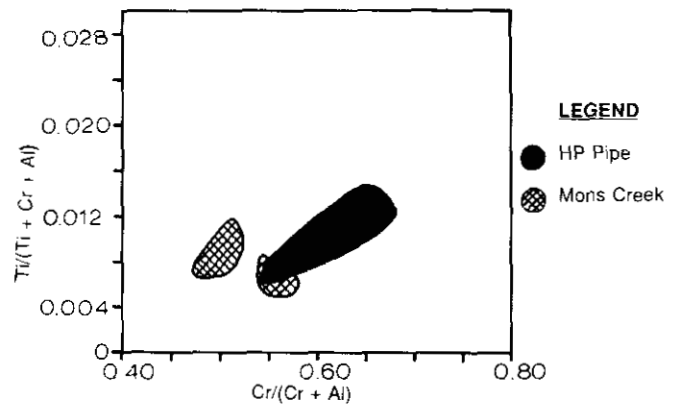


Figure 1-4-6. Plot of $\text{Cr}\#$ versus $\text{Ti}\#$ indicating a positive correlation for HP spinels and a negative correlation for Mons Creek high- $\text{Cr}\#$ spinels.

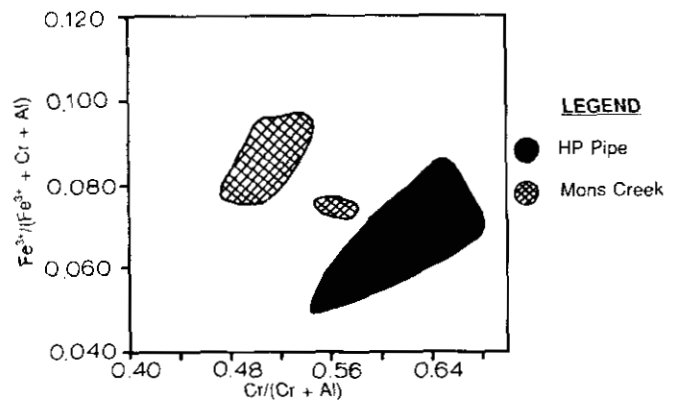


Figure 1-4-7. Plot of $\text{Cr}\#$ versus $\text{Fe}^{3+\#}$ indicating a positive correlation for the HP and Mons Creek low- $\text{Cr}\#$ spinels and a negative correlation for the high- $\text{Cr}\#$ spinels.

groundmass, and only rarely are olivines or olivine pseudomorphs found among the phenocryst phases at Mons Creek. The clinopyroxenes also show a bimodal chemical pattern, with either increasing or decreasing aluminum and titanium relative to $\text{Mg}\#$, and zoning is either "normal" or "reverse". Thus both the magnesiochromites and clinopyroxenes suggest either two different processes or they are the result of two provenances with mixing of two initially separate magmas.

Other bimodal patterns exist among the Mons Creek magnesiochromites. In the $\text{Cr}\#$ versus $\text{Fe}^{3+\#}$ graph, a positive correlation is found at lower $\text{Cr}\#$ values and a negative correlation at higher $\text{Cr}\#$ values (Figure 1-4-7; Table 1-4-3). The positive correlation segments at lower $\text{Cr}\#$ suggest plagioclase-plus-olivine fractionation similar to the interpretation in Figure 1-4-5. The negative correlation segments at higher $\text{Cr}\#$ may reflect the olivine fractionation process similar to the interpretation in Figure 1-4-5. The higher $\text{Cr}\#$ magnesiochromites are in equilibrium with olivine of higher forsterite content. Possibly this group of magnesiochromites is the result of increased mantle melting followed by olivine fractionation. This lends support to the hypothesis of increased partial melting with increasing $\text{Cr}\#$. Mixing of

TABLE 1-4-3
SPINEL CORRELATIONS

	Fe ²⁺ # vs Cr#	Cr# vs Ti#	Cr# vs Fe ³⁺ #	Fe ²⁺ # vs Ti#
HP Pipe	0.68	0.69	0.42	0.24
Mons Creek high Cr	-0.91	-0.56	-0.53	0.47
low Cr	0.59	0.21	0.37	0.39

fractionated material with more primitive chrome and magnesium-rich material is consistent with the clinopyroxene trend for the Mons Creek pipe.

The Mons Creek high-Cr# spinels exhibit a negative correlation between Cr# and Ti#, also consistent with an increased mantle melting interpretation, while the low-Cr# lobe has a very low correlation with Ti#. Taking both lobes together indicates an overall negative correlation between Cr# and both Ti# and Fe³⁺#. These trends are consistent with an increased mantle melting interpretation.

In summary, the chemical trends of the Mons Creek magnesiocromites exhibit both fractionation and increased mantle melting processes similar to the conclusions reached from the clinopyroxene chemical trends.

The chemical composition and trends of the Golden lamprophyre magnesiocromites are similar to those in ultramafic lamprophyres, lamproites and peridotites. Spinel compositions and trends do not unequivocally indicate their origins, as there is much variation within each rock type. The magnesiocromites may be merely disaggregations from a solid peridotitic rock or they may be crystallization products from a hydrated (metasomatized) peridotitic melt which formed the lamprophyre. In either case their chemical composition would be similar. Clear evidence of entrained xenoliths was not seen in thin section. The grains occur singly or rarely as inclusions in olivine pseudomorphs, are subhedral to rounded, and range from phenocryst to microphenocryst in size, all of which may be evidence of crystallization from a melt. Although compatible with a xenocrystic interpretation, the inferences drawn from spinel chemical trends are consistent with inferences drawn from cognate clinopyroxene trends: fractionation and increased mantle partial melting at the HP and Mons Creek pipes.

SUMMARY OF IGNEOUS PROCESSES

In the HP pipe, the combined chemical trends of the pyroxenes and spinels corroborate the idea that two processes are involved. Fractionation is clearly indicated by the inverse relationship of Mg# versus Ti cations in high and intermediate-Mg# clinopyroxene trends and is supported by the spinel chemical trends of increasing Ti# and Fe³⁺#. The subsequent influx of primitive magma, as a result of increased partial mantle melting prior to emplacement, is indicated by the reversely zoned clinopyroxenes and by the increased chrome contents of the spinels.

Mineral chemical data from the Mons Creek pipe are somewhat more complex. The Mons Creek clinopyroxenes have oscillatory zoning indicative of at least two magma pulses, fractionation and mixing involving both cognate and xenocrystic material. The spinel data also indicate a bi-

modal origin and two distinct fractionation patterns. Both the HP and the Mons Creek pipes incorporate high-iron clinopyroxene xenocrysts.

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