

# Geology of the Quartet Mountain lamprophyre suite, Wernecke Mountains, Yukon

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Milidragovic, D., Thorkelson, D.J. and Marshall, D.D., 2006. Geology of the Quartet Mountain lamprophyre suite, Wernecke Mountains, Yukon. *In: Yukon Exploration and Geology 2005*, D.S. Emond, G.D. Bradshaw, L.L. Lewis and L.H. Weston (eds.), Yukon Geological Survey, p. 231-245.

## ABSTRACT

The Early Cambrian Quartet Mountain lamprophyres are volatile-rich ultramafic alkaline dykes that cross-cut the Wernecke and Mackenzie mountains supergroups in the Wernecke Mountains of northern Yukon. Their emplacement may have been triggered by Early Paleozoic extension of the Cordilleran miogeocline. Numerous small-volume alkalic igneous rocks that range in age from Cambrian to Devonian occur elsewhere in the miogeocline and may reflect a similar tectonic setting. The Quartet Mountain lamprophyres contain phenocrysts of phlogopite  $\pm$  diopside  $\pm$  olivine within a dark-grey aphanitic groundmass and were likely generated by low-percentage melting of mantle at depths  $>90$  km. One of the lamprophyres contains abundant pseudomorphed olivine xenocrysts and xenoliths of inferred crustal and mantle affinities. Although this dyke resembles kimberlite because of its abundance of mantle xenoliths and xenocrysts and its ultramafic composition, it differs from kimberlite in its abundance of phlogopite phenocrysts. It is best described as an ultramafic lamprophyre with kimberlitic affinity. The lamprophyres have modest potential to host diamonds.

## RÉSUMÉ

Les lamprophyres de Quartet Mountain du Cambrien précoce sont organisés en filons intrusifs alcalins ultrabasiques riches en composants volatils recoupant les supergroupes de Wernecke et de Mackenzie Mountains dans les monts Wernecke du Yukon septentrional. Leur mise en place fut possiblement déclenché lors de l'extension du miogéocline de la Cordillère au Paléozoïque précoce. Un grand nombre de masses de roches ignées alcalines de petit volume et d'âges s'étendant du Cambrien au Dévonien se retrouvent aussi ailleurs dans le miogéocline, ce qui peut refléter un environnement tectonique similaire. Les lamprophyres de Quartet Mountain sont gris-sombre, à matrice aphanitique avec cristaux dispersés de phlogopite  $\pm$  diopside  $\pm$  olivine et ont vraisemblablement été générés par fonte d'une faible proportion du manteau à des profondeurs excédant 90 km. Un des lamprophyres contient d'abondants xénocristaux d'olivine pseudomorphe et des xénolites présumés d'origines crustales et mantelliques. Malgré que ce filon, de par son abondance en xénolites et xénocristaux mantelliques et sa composition ultrabasique, ressemble aux kimberlites, son abondance en phénocristaux de phlogopite le distingue de celles-ci. On le dénommera ainsi lamprophyre ultrabasique à affinités kimberlitiques. Les lamprophyres ont un potentiel diamantifère limité.

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## INTRODUCTION

Early to Middle Paleozoic alkalic igneous rocks have been reported from numerous localities in the northern Cordilleran miogeocline from Alaska to southwestern Alberta (Cecile, 1982; Godwin and Price, 1986; Roots, 1988; Cecile and Norsford, 1992; Goodfellow *et al.*, 1995; Abbott, 1997). The igneous rocks consist of spatially restricted volcanic successions and small intrusions of alkalic to ultrapotassic composition and are interpreted to represent continental rift magmatism (Roots, 1988; Goodfellow *et al.*, 1995). Mid-Paleozoic mafic to ultramafic diatremes, at least one of which was interpreted to be a kimberlite, occur in the Mackenzie Mountains of western Northwest Territories (Godwin and Price, 1986). Late Ordovician to Mississippian, mafic, alkaline intrusions, including carbonatites, lamprophyres, lamproites and kimberlites, occur in a narrow, north-west trending belt that straddles the boundary of the Omineca and Foreland belts, along the length of British Columbia (Pell, 1994; Simandl, 2004). Kimberlites of Cambrian and Siluro-Ordovician ages are exposed to the east of the miogeocline in the Slave province of Northwest Territories (Heaman *et al.*, 2004) but are not demonstrably related to extension.

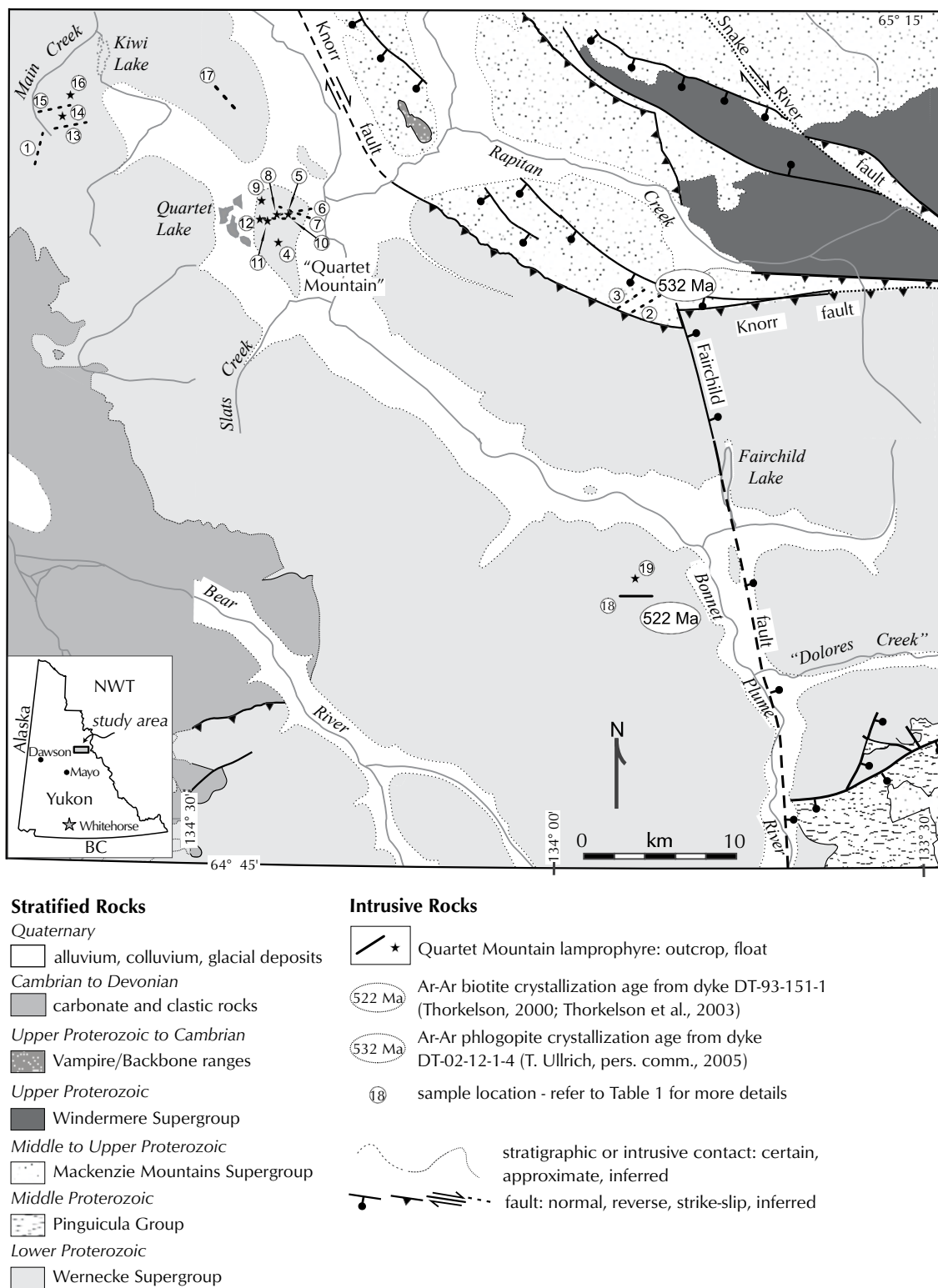
This paper provides new information on the Quartet Mountain lamprophyres (Thorkelson *et al.*, 2003), a set of ultramafic alkaline volatile-rich intrusions that cross-cut the Wernecke and Mackenzie mountains supergroups in the Wernecke Mountains of northern Yukon. They are exposed in a region between Fairchild Lake and Kiwi Lake, herein called the study area (Fig. 1). At least three members of the suite host abundant xenoliths of apparent mantle and crustal affinity. The lamprophyres and their xenoliths have potential to provide new and important information on the mantle and crustal conditions of northern Yukon at the time of their emplacement. Two preliminary  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  biotite and phlogopite dates indicate that the lamprophyres are early Cambrian (Fig. 1). One of the dates (ca. 522 Ma) was reported by Thorkelson (2000; see clarification in Thorkelson *et al.*, 2003) and the other (ca. 532 Ma) was recently obtained from the Pacific Centre for Geochemical and Isotopic Research (T. Ullrich, pers. comm., 2005). Two previous K-Ar dates of  $552 \pm 13$  Ma and  $613 \pm 15$  Ma (Delaney, 1981) suggest that the lamprophyres could be as old as Neoproterozoic. However, these ages are considered to be less accurate than the  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  ages and for that reason we interpret the lamprophyres as early Cambrian. Additional

geochronology is underway to more thoroughly address the age-range of the lamprophyres.

## GEOLOGICAL SETTING

Emplacement of the Quartet Mountain lamprophyres took place during early development of the Paleozoic miogeocline of ancestral North America (Laurentia). The crustal architecture of the northern part of this miogeocline was largely inherited from Neoproterozoic rifting and concurrent deposition of the Windermere Supergroup. Several discrete episodes of rifting began at ca. 780 Ma and may have separated Laurentia from another continent (Ross, 1991; Colpron *et al.*, 2002; Harlan *et al.*, 2003). Along the northern proto-Pacific margin, extension and associated magmatism primarily occurred early in the history of Windermere deposition (Armstrong *et al.*, 1982; Roots and Parrish, 1988; Jefferson and Parrish, 1989; Heaman *et al.*, 1992; Dudas and Lustwerk, 1997). The basal Coates Lake and Rapitan groups were deposited in fault-bounded basins and embayments (Eisbacher, 1977; Jefferson, 1978) and were overlain by strata which record a transition from rift to continental shelf on a prograding passive margin (MacNaughton *et al.*, 2000). In the Early Cambrian, renewed extension led to further rifting of western Laurentia and division of the continental margin into deep clastic basins flanked by shallow carbonate platforms. The Quartet Mountain lamprophyres were emplaced into one of these shallower-water regions known as the Mackenzie Platform (Lenz, 1972). Extensional faulting continued sporadically until the Middle-Jurassic, when terrane collision led to imbrication and folding the miogeoclinal succession (Gordey and Anderson, 1993). Paleozoic magmatic activity, which occurred episodically from Cambrian until Late Devonian (Goodfellow *et al.*, 1995), is apparently related to the extension.

The northern Cordilleran miogeocline hosts minor Cambrian to Devonian alkaline to ultrapotassic igneous rocks that form thin, laterally restricted volcanic piles and intrusions along most of its strike length. In addition to the Quartet Mountain lamprophyres, known Paleozoic igneous rocks in the Mackenzie-Ogilvie platform are the Silurian Mountain, Bear and Stib diatremes (Godwin and Price, 1986) and the poorly studied Nash, Tuk and Silurian volcanics (unit Sv of Abbott, 1997). Godwin and Price (1986) proposed that the Mountain diatreme is a kimberlite, based on mineral chemistry and diagnostic indicator minerals, including micro-diamonds. The



**Figure 1.** Geological map of the study area showing locations of the Quartet Mountain lamprophyres; modified from Gordey and Makepeace (2003), Schwab and Thorkelson (2000) and Thorkelson et al. (2005).

mineralogical and textural characteristics of the diatreme, however, are different from most kimberlites. Abundant volcanic rocks are exposed in the Selwyn Basin, a major paleogeographic element which lies to the southwest of the Mackenzie Platform. Geochemical data from these rocks are consistent with paleotectonic models of the Selwyn Basin that characterize it as a passive continental rift that underwent episodic reactivation from the Cambrian to Late Devonian (Cecile, 1982; Gordey and Anderson, 1993; Goodfellow *et al.*, 1995). Major volcanic episodes occurred in the Selwyn Basin in the Cambrian, Early to Middle Ordovician and Middle to Late Devonian (Goodfellow *et al.*, 1995). In British Columbia, temporal distribution of alkaline diatremes that include carbonatites, kimberlites, lamproites, lamprophyres and nepheline syenites indicate that they formed during three major periods of rifting in the Late Ordovician to Silurian, Early Devonian and Late Devonian (Pell, 1994).

## QUARTET MOUNTAIN LAMPROPHYRE LOCATIONS AND FIELD RELATIONS

### PREVIOUS WORK

Lamprophyres in the Wernecke Mountains were documented by several workers but have not been studied in detail. Locations and ages of the confirmed Quartet Mountain lamprophyres are provided in Table 1. Delaney (1981) first reported lamprophyres in the Wernecke Mountains in the vicinity of Kiwi Lake (Fig. 1). Hulstein (1994) mapped lamprophyres near the Gremlin and Chloe mineral occurrences in the same area. A few kilometres to the southeast, Laznicka and Gaboury (1988) recorded fine-grained grey weathering, tan to light-brown, olivine-biotite lamprophyres on the western and northern slopes of Quartet Mountain, a prominent and informally named feature west of the Bonnet Plume River (Fig. 1). They reported perovskite phenocrysts up to 1 cm long, but this finding has not yet been verified. Thorkelson and Wallace (1994) reported two biotite-phyric andesite dykes approximately 7 and 10 km southwest of Fairchild Lake (Fig. 1). Subsequently, Thorkelson *et al.* (2003) noted

**Table 1.** Locations of Quartet Mountain lamprophyres and available field measurements.

Sample	Lamprophyre field number	Location		1:50 000 NTS map sheet	Orientation (degrees)	Width (m)
		Easting	Northing			
1	DM-05-01-1-2	514617	7226946	106E/2	015/80	1.5
2	DT-02-12-1-4	546987	7219808	106F/4	240/85	0.15
3	DM-05-03-2-3	546610	7219902	106E/1	232/60	0.8
4	DM-05-04-1-1	528748	7222915	106E/1	float on top of ridge	-
5	DM-05-04-2-1	528950	7223483	106E/1	toppled	0.85
6	DT-02-7-1-1	529033	7223487	106E/1	290/80	2
7	DT-02-7-3-1	529033	7223487	106E/1	080/70	1.75
8	RBI-05-01-1-1	528607	7223554	106E/1	talus	-
9	DM-05-05-1-1	528037	7223962	106E/1	talus	-
10	DM-05-06-2-1	528632	7223374	106E/1	090/89	0.8
11	DM-05-06-3-1	528478	7223438	106E/1	float on top of ridge	-
12	DM-05-06-4-1	528273	7223543	106E/1	float on top of ridge	-
13	DM-05-07-1-1	516530	7227670	106E/2	260/89	1.2
14	DM-05-07-2-1	516037	7228640	106E/2	-	-
15	DM-05-07-4-1	515768	7229922	106E/2	steeply dipping at 255	1.5
16	TOA-96-8-1	516399	7230074	106E/2	float on top of ridge	-
17	DT-02-9-4-1	524225	7231523	106E/1	140/80	1-2
18	DT-93-151-1	553466	7197871	106C/13	270/90	-
19	-	-	-	106C/13	-	-

several dykes on and near Quartet Mountain and described them as brown-weathering, mafic, clinopyroxene- and phlogopite-phyric lamprophyres. Thorkelson *et al.* (2003) also noted a xenolith-rich lamprophyre dyke approximately 7 km south of Rapitan Creek, east of the Bonnet Plume River (Fig. 1). Thorkelson *et al.* (2003) assigned all the dykes mentioned above to a single igneous suite named the Quartet Mountain lamprophyres. We retain this name and extend it to additional lamprophyre localities described below.

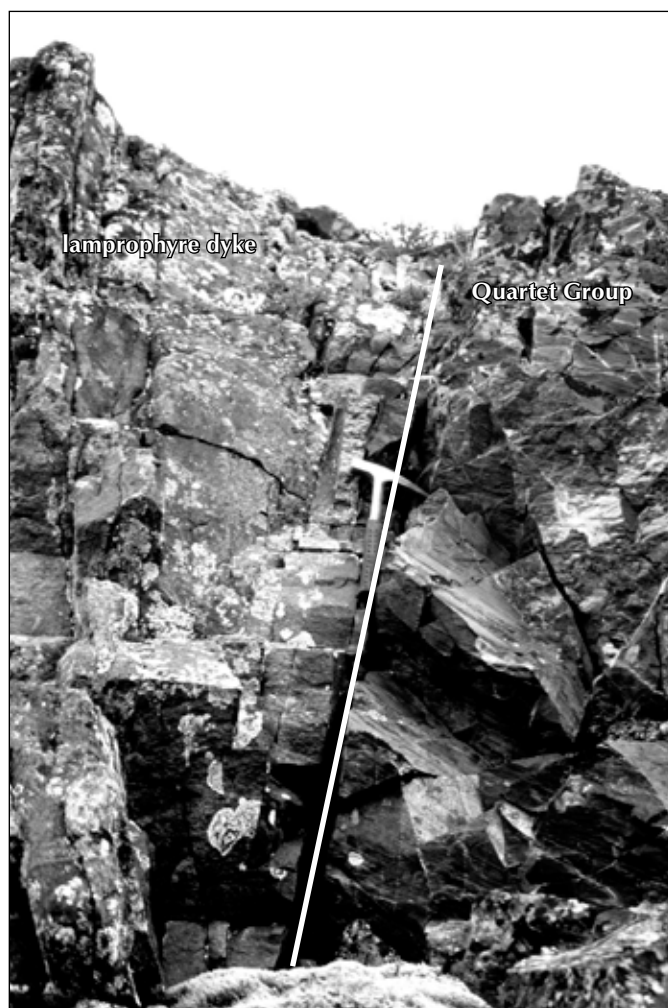
### RECENTLY DISCOVERED LOCALITIES

In July 2005, eleven new lamprophyres were discovered in a mountainous area southwest of Kiwi Lake and on the northern and western slopes of Quartet Mountain. In addition, two xenolith-rich lamprophyres south of Rapitan Creek previously identified by Thorkelson *et al.* (2003), were examined and sampled. Overall, approximately 200 kg of rock were collected for petrographic, geochemical, isotopic, and geochronological studies.

### FIELD RELATIONS

The field information for all of the known Quartet Mountain lamprophyres is summarized in Table 1. North of Knorr fault (Fig. 1), the lamprophyres cross-cut the carbonate rocks of Mesoproterozoic to Neoproterozoic Mackenzie Mountains Supergroup. South of the Knorr fault the lamprophyres cross-cut the Paleoproterozoic metasedimentary rocks of the Wernecke Supergroup.

The lamprophyres are steeply dipping, range in width from 15 cm to 2 m (Fig. 2), and strike in a general east or southeast direction. The contact between the dykes and their host rocks ranges from sharp and regular to poorly defined and irregular. Intrusion of the dykes was partly controlled by pre-existing foliations or fractures in the host rock. Four of the eleven newly discovered dykes were observed in outcrop, whereas the other seven were observed as float. The lamprophyres are more prone to weathering and erosion than their host rocks, and commonly form trains of float on steep mountain sides. Abundant lamprophyre talus on the northern and western slopes of Quartet Mountain suggests that numerous dykes were emplaced in this area and lie beneath shallow talus and felsenmeer.



**Figure 2.** Sharp contact between steeply dipping lamprophyre DT-02-7-1-1 and laminated Quartet Group metasedimentary rocks.

### LAMPROPHYRE PETROGRAPHY

Petrographic analysis of the Quartet Mountain lamprophyres was carried out using a combination of hand-sample analysis, conventional petrographic microscopy, and scanning electron microscopy (SEM). To date, only samples 2, 6, 7, 16, 17 and 18 have been petrographically characterized (Table 1). Sample 2 is texturally and mineralogically distinct from the rest of the suite and has some features that are characteristic of kimberlite. This sample is discussed in a separate section below.

The Quartet Mountain lamprophyres are light to dark grey, brown weathering, and porphyritic. In rare instances they contain abundant mafic xenoliths up to 4 cm in diameter (Fig. 3). The phenocrysts range from euhedral to anhedral,



**Figure 3.** Steeply dipping lamprophyre DM-05-03-2-3 hosting abundant mafic xenoliths. The xenoliths are concentrated near the centre of the dyke. Carbonate vein cuts the dyke (arrow).

vary in abundance, and include phlogopite, bladed diopside and equant pseudomorphed olivine. Apatite and unidentified opaque phenocrysts vary in abundance. Some samples contain abundant 0.2- to 3-mm-diameter amygdules that are filled with sparry carbonate and opaque minerals. Groundmass is pervasively altered to chlorite, clay and carbonate. Phlogopite and minor opaque minerals are the only primary groundmass minerals. It is unclear whether carbonate minerals in the groundmass are of primary or secondary origin.

The modal phlogopite abundance in the suite varies from 10-35%. The phlogopite phenocrysts are up to 3 mm long, are anhedral to euhedral, and commonly enclose diopside or opaque mineral inclusions. Phlogopite is variably altered to chlorite and a bright red mineral, possibly

hematite, and is commonly embayed. Modal diopside abundance ranges from 7-32%. The diopside grains are euhedral and commonly form radial aggregates. Chlorite alteration of diopside is common, but generally confined to crystal edges. Pseudomorphed olivine is an important phenocrystic and xenocrystic phase in most Quartet Mountain lamprophyres. No relict olivine was recorded in any of the samples, as it has been completely replaced by chlorite, carbonate and various opaque minerals. Distinction between xenocrystic and phenocrystic olivine was made on the basis of crystal size and shape. Olivine interpreted as xenocrysts is generally rounded to sub-rounded, whereas olivine interpreted as phenocrysts is euhedral. Diopside overgrowths occur on some olivine xenocrysts. With the exception of sample 2, the modal amount of pseudomorphed olivine ranges from 0 to 8%. The opaque phases include Ti-rich magnetite, pyrite, rutile and spinel and occur as both primary and secondary groundmass and phenocryst grains. They typically comprise a minor component of the rock mass. Apatite is euhedral, up to 0.5 mm long, and ranges in modal abundance from 1-2.5%.

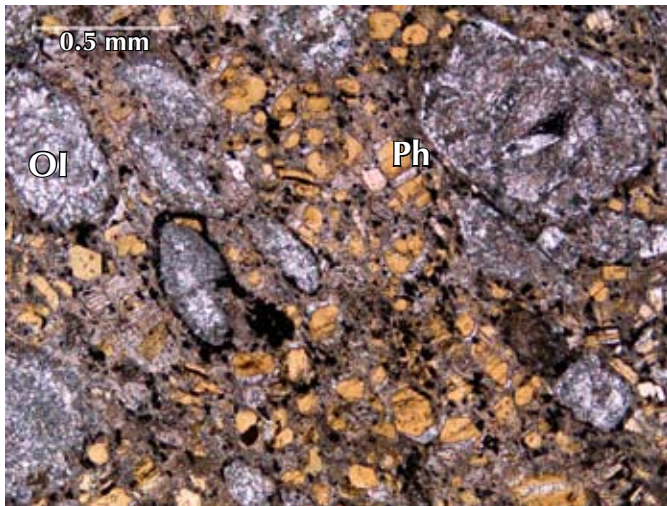
Chemical compositions of major mineral phases of the Quartet Mountain lamprophyre suite were qualitatively determined using the energy dispersive analysis x-ray (EDAX) method at Simon Fraser University. Phlogopite in sample 6 was nearly pure phlogopite with sub-equal amounts of Fe and Ti substituting for approximately 5% of Mg.

The approximate formula of  $\text{Ca}_{12}\text{Mg}_{0.6}\text{Fe}_{0.2}\text{Si}_2\text{O}_6$  for diopside was determined using EDAX.

Groundmass typically makes up approximately 30 to 40% of the whole rock mode in the Quartet Mountain lamprophyres. The pervasive replacement of groundmass minerals makes the Quartet Mountain lamprophyres impossible to classify according to the petrographic criteria of Rock (1987, 1991) or the International Union of Geological Sciences (Le Maitre, 2002), which require knowledge of both phenocryst and groundmass mineralogy. Consequently, the lamprophyres were classified on the basis of chemical composition in the geochemistry section below.

## LAMPROPHYRE SAMPLE 2

Sample 2 (Table 1) differs from other samples of Quartet Mountain lamprophyre by its strong textural and mineralogical similarities to kimberlite, most notably the inequigranular texture and abundance of anhedral



**Figure 4.** Pseudomorphed olivine macrocrysts (Ol) in fine groundmass composed of euhedral phlogopite (Ph), clay and carbonate (sample 2). Euhedral phlogopite groundmass crystals are uncommon in type I kimberlites.

xenocrystic olivine (Fig. 4). The three main petrographic components of this sample are xenoliths, large mineral grains (>0.5 mm) collectively termed macrocrysts, and groundmass.

The xenoliths are variably distributed in sample 2 and tend to occur in clusters. Three general types of xenoliths were identified. These are angular to sub-angular carbonate xenoliths of the Mackenzie Mountains Supergroup, crustal xenoliths of high metamorphic grade and mantle xenoliths. The latter two are discussed in greater detail in subsequent sections.

The macrocryst assemblage is composed of carbonate and chlorite pseudomorphs after olivine, phlogopite, and minor opaque minerals that include chromian spinel and rutile. The pseudomorphed olivine macrocrysts are inferred to be xenocrysts derived from disaggregation of peridotite xenoliths. The olivine macrocrysts show mesh texture that suggests serpentinization preceded carbonate replacement. Phlogopite grains are commonly euhedral and are therefore thought to be phenocrysts that were in equilibrium with the melt. Bent and kinked phlogopite grains, showing visible parting along the cleavage planes, are scattered throughout the rock and are probably xenocrysts. One phlogopite grain has oscillatory zoning, with an inner rim enriched in Mg and an outer rim and core depleted in Fe and Ti. EDAX shows that chromium content decreases outward toward the rim and that the inner rim is compositionally most similar to the phlogopite

from sample 6. The EDAX-estimated chemical formula of a chromian spinel macrocryst from sample 2 is  $Mg_{0.67}Fe_{0.33}AlCrO_4$ . The groundmass mineral assemblage consists of euhedral phlogopite, anhedral to euhedral opaque minerals, chlorite, clay and carbonate. Olivine and diopside are notably absent from groundmass.

The most striking characteristic of sample 2 is the presence of rounded anhedral olivine macrocrysts of variable size set in a fine-grained matrix. This texture is characteristic of kimberlites (Mitchell, 1986). Despite this similarity, other textural features and some important mineralogical characteristics of sample 2 differ from those of kimberlites. Specifically, the high abundance of cognate phlogopite and the apparent lack of microphenocrystic and groundmass olivine are inconsistent with type I kimberlites (Mitchell, 1986, 1995). The absence of groundmass or microphenocrystic diopside is atypical of type II kimberlites (Mitchell, 1995). We classify sample 2 as an ultramafic lamprophyre with kimberlitic affinity.

#### PETROGRAPHIC CHARACTERISTICS OF MANTLE XENOLITHS

The mantle xenoliths are well-rounded, grey-green to black, commonly elongated mafic inclusions up to 5 cm long (Fig. 5). An accurate mineral mode for the xenoliths could not be established, because alteration and replacement of primary minerals by serpentine, clay and carbonate minerals is near-complete. The xenoliths were most likely dominated by olivine, a conclusion supported in part by the ubiquitous pseudomorphed olivine xenocrysts. Minor, relict orthopyroxene grains, up to 3 mm in diameter stand out in serpentinized inclusions. EDAX indicates that the composition of these grains is



**Figure 5.** Dark green, ovoid, serpentinized mantle xenolith (circled) from sample 2.

approximately  $En_{95}$ . Most grains are partly altered to sericite and are unusually rich in potassium. Trace relict clinopyroxene was identified in one xenolith. Another xenolith contains abundant garnet. Opaque minerals that include pyrite and hematite account for approximately 20% of the mantle xenolith mode. Growth of secondary phlogopite near the xenolith margins is a consequence of reaction between the lamprophyre melt and the entrained inclusions. On the basis of observed mineralogy, the Early Cambrian upper mantle in this region was composed of, at least in part, garnet-peridotite.

### PETROGRAPHIC CHARACTERISTICS OF CRUSTAL XENOLITHS

The crustal xenoliths are less abundant than the mantle xenoliths, but are generally better preserved, allowing for more accurate characterization. They occur as rounded inclusions of garnet-sillimanite-quartz gneiss (Fig. 6), garnet-quartz gneiss, and foliated plagioclase-rich metamorphic rock.

The garnet-sillimanite-quartz gneiss contains thin bands (<2 mm) of fine-grained, quartz crystals. The quartz grains are locally separated by a thin hematite film. Within the quartz bands, small (20  $\mu\text{m}$ -120  $\mu\text{m}$ ), well-rounded, isolated grains of zircon occur. Individual quartz bands are separated by equally thin discontinuous bands of garnet and sillimanite. The garnet grains are irregularly shaped and heavily fractured. Chlorite and iron-oxide lines the fractures. Garnet composition was estimated, using EDAX, as 60% pyrope and 40% almandine with minor Ca. Garnet forms bands on its own, or in association with sillimanite. Sillimanite grains are irregular, approximately 0.05 mm in diameter and set in a potassium feldspar groundmass. Monazite, rutile and zircon occur as isolated grains within the garnet grains, or

as isolated interstitial minerals in association with both garnet and sillimanite.

The gneissic xenoliths are pervasively altered along their margins, where a combination of calcite, phlogopite, hematite, clay and/or sericite replaced all minerals except quartz. The gneiss is cut by calcite veinlets that are truncated at the xenolith margins, indicating that the veining predated the incorporation of xenoliths into the lamprophyre magma.

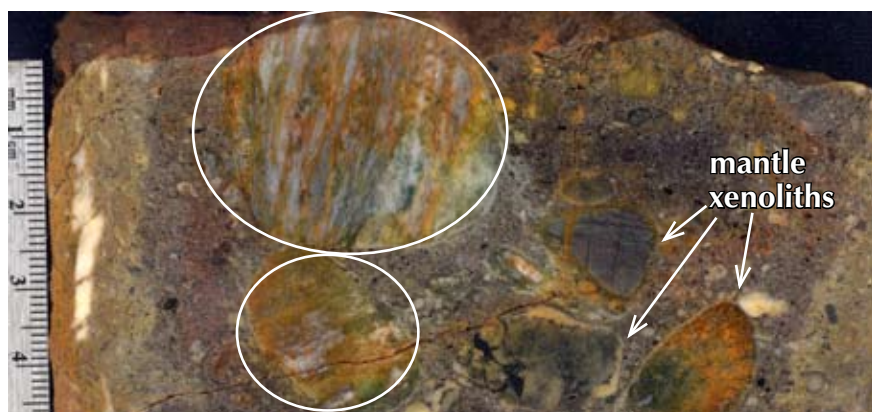
A single feldspathic xenolith was identified in sample 2. The feldspathic xenolith is composed of sub-parallel laminae of polygonal to irregular-shaped feldspar grains, thin carbonate laminae and minor, very thin, opaque laminae. The feldspar layers are compact, 0.5-2 mm wide, and contain a few percent interstitial opaque minerals. The feldspar is dominantly plagioclase, and grains range in size from 0.1- 0.9 mm. The carbonate laminae are approximately 0.2 mm thick.

### GEOCHEMISTRY

Geochemical data exist for five of the eighteen known Quartet Mountain lamprophyres (Table 2; Thorkelson, 2000; Milidragovic, 2005). The major element contents that are discussed in this and the following sections have been normalized to a volatile-free basis (data are not normalized in Table 2, but values discussed in text are normalized).

### MAJOR ELEMENT GEOCHEMISTRY

The Quartet Mountain lamprophyres are characterized by high volatile contents that range between 4.7 and 24.8%. Volatile content of samples 6, 7, 16 and 18 is probably dominated by  $\text{H}_2\text{O}$ , as carbonate alteration is minor, and hydrous minerals such as chlorite and phlogopite are



**Figure 6.** Finely banded, garnet-sillimanite-quartz gneiss xenolith (circled) in sample 2. Darker, serpentinized mantle xenoliths are located in the right half of the photograph.



abundant. The higher volatile content of sample 2 is likely a result of the greater abundance of xenoliths and xenocrysts, most of which are rich in carbonate and/or hydrous minerals, and thus probably contain significant H<sub>2</sub>O and CO<sub>2</sub>. Whole rock Mg numbers, defined as atomic Mg / (Mg + Fe)\*100, of the Quartet Mountain

lamprophyre suite range from 63 to 86. The suite is silica-undersaturated, and has SiO<sub>2</sub> contents that vary from 32.3% to 43.4%, and normative nepheline contents that range from 0.37 to 5.28 wt.%. The high P<sub>2</sub>O<sub>5</sub> concentration in sample 16 is consistent with its high apatite content. The suite plots in the alkaline field on the

**Table 2.** Major and trace element data from the Quartet Mountain lamprophyres. Data have not been normalized to a volatile-free basis. Data for sample 18 is from Thorkelson (2000). Data for samples 2, 6, 7 and 16 is from Milidragovic (2005).

	Sample number				
	2	6	7	16	18
Major oxides (wt%)					
SiO <sub>2</sub>	23.78	39.63	40.19	31.03	37.40
TiO <sub>2</sub>	1.420	3.259	3.287	3.760	3.500
Al <sub>2</sub> O <sub>3</sub>	2.83	7.8	8.34	6.33	6.62
FeO					6.8
Fe <sub>2</sub> O <sub>3</sub>	7.56	13.00	13.19	13.47	14.10
MnO	0.12	0.19	0.26	0.31	0.44
MgO	19.43	15.38	14.73	14.18	16.00
CaO	16.29	11.50	11.39	14.82	9.20
Na <sub>2</sub> O	0.06	1.07	0.87	0.18	0.46
K <sub>2</sub> O	1.89	1.37	1.03	2.60	1.01
P <sub>2</sub> O <sub>5</sub>	1.01	0.63	0.69	1.95	0.86
LOI	24.80	4.71	4.95	10.20	7.25
Trace elements (ppm) NOTE: * - ppb ** - wt.%					
Cs	3.47	2.74	3.65	3.33	3.12
Tl	0.34	0.15	0.14	0.12	0.15
Rb	86.2	43.62	31.96	91.74	38.31
Ba	1204	983	543	2160	4263
W	6	-1	2	1.82	
Th	29.47	6.91	7.16	23.17	8.74
U	4.69	1.73	1.75	3.85	2.42
Nb	168.59	84.41	89.31	157.29	122.42
Ta	7.86	5.02	5.27	8.12	5.94
La	194.44	56.02	59.42	194.54	66.78
Ce	360.11	111.31	118.65	380.45	134.02
Pb	13.52	11.45	9.42	-5	6.38
Pr	39.06	12.96	13.75	37.33	16.21
Sr	1544	432	388	950.9	845.83
Nd	138.54	51.9	54.0	157.25	64.24
Sm	20.30	10.85	11.57	26.29	12.12
Zr	258.41	259.96	268.49	354.39	317.77
Hf	6.47	6.64	6.53	8.82	7.59
Eu	4.90	3.01	3.25	6.44	3.58

	Sample number				
	2	6	7	16	18
Major oxides (wt%)					
Sn	1.66	2.44	3.59	2.00	3.14
Sb	0.9	0.8	0.9	0.71	1.61
Gd	11.84	8.24	8.56	18.6	11.11
Tb	1.46	1.18	1.22	2.25	1.23
Dy	5.59	5.09	5.32	9.56	6.53
Y	20	21	22	41.5	24.64
Ho	0.79	0.78	0.81	1.4	1.03
Er	1.82	1.86	2.06	3.44	2.26
Tm	0.21	0.23	0.25	0.305	0.30
Yb	1.23	1.37	1.45	1.87	1.44
Lu	0.13	0.17	0.17	0.259	0.19
Zn	80.27	106.53	109.09	302	408.04
V	100	248	250	220	321.7
Sc	20.1	27.5	24.1		23.84
Co	74.2	84.1	86.1	97.1	84
Cu	18.92	67.16	63.69	-5	19.37
Cr	1220	734	736	364	851
Ni	744	457	458	412	591
Ag	-0.3	0.6	0.4	-0.5	
Cd	-0.3	-0.3	-0.3		
Au*	3	-1	6		
As	8	3	4	8	
Br	-0.5	-0.5	-0.5		
Hg	-1	-1	-1		
Ir*	-1	-1	-1		
Mo	-2	-2	2	1.5	
Se	-0.5	-0.5	-0.5		
Ga	9.1	19.4	20.9	19	
Ge	2.8	1.4	1.4	1.4	
In	-0.1	-0.1	-0.1	0.1	
Sn	1.658	2.438	3.595	2	
S**	0.093	0.124	0.284		

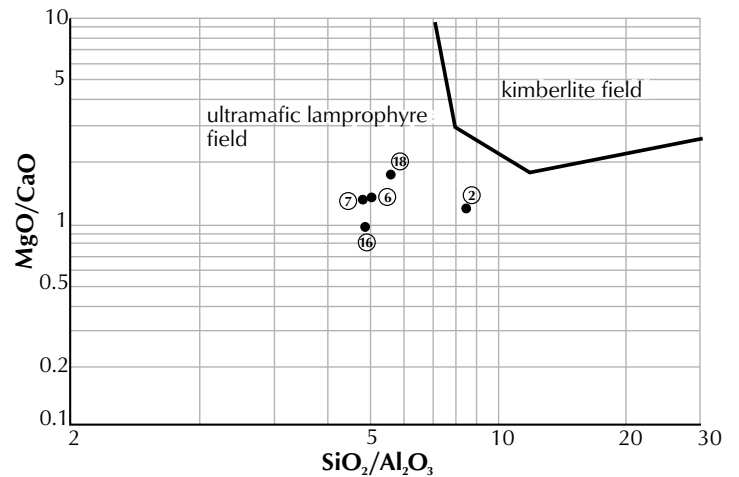
total alkali vs. silica diagram (Irvine and Baragar, 1971). Xenolith-poor samples 6, 7, 16 and 18 show positive correlation between  $Al_2O_3$ ,  $Na_2O$  and  $SiO_2$ , and negative correlation between  $SiO_2$ ,  $TiO_2$  and  $K_2O$ .

The ultramafic character and presence of normative nepheline precludes the Quartet Mountain lamprophyres from being classified as calc-alkaline lamprophyres of Rock (1987, 1991). This is further supported by the positive Ta-Nb ± Ti anomaly (see trace element geochemistry section below) that is characteristic of the suite, but highly uncharacteristic of calc-alkaline lamprophyres. The metaluminous composition of the Quartet Mountain lamprophyres is inconsistent with the characteristically peralkaline composition of lamproites. The Quartet Mountain lamprophyres are best classified as ultramafic lamprophyres rather than alkaline lamprophyres (Fig. 7). None of the Quartet Mountain lamprophyres plot in the kimberlite field of Figure 8.

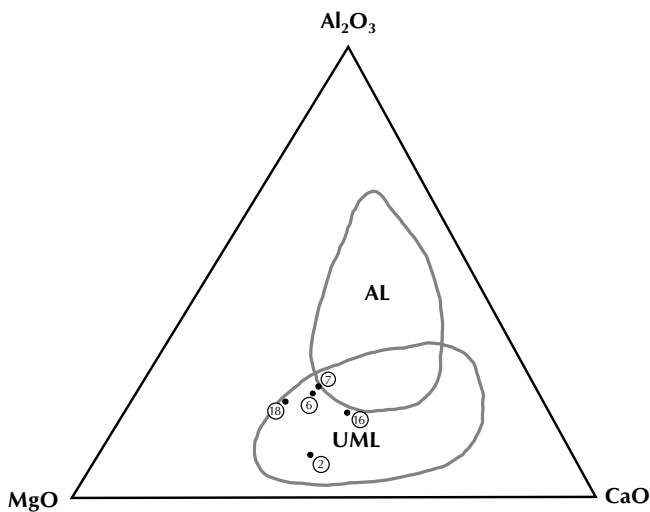
**TRACE ELEMENT GEOCHEMISTRY**

The Quartet Mountain lamprophyres are enriched in all trace elements (Fig. 9) relative to the primitive mantle values of Sun and McDonough (1989). Although the enrichment factors within the suite vary by as much as 10 times for the most incompatible elements (e.g., Ba), the overall trace element patterns throughout the suite are very similar. The concentrations of the highly mobile, large ion lithophile elements likely reflect post-emplacment processes, which are evidenced by pervasive groundmass alteration; hence, their

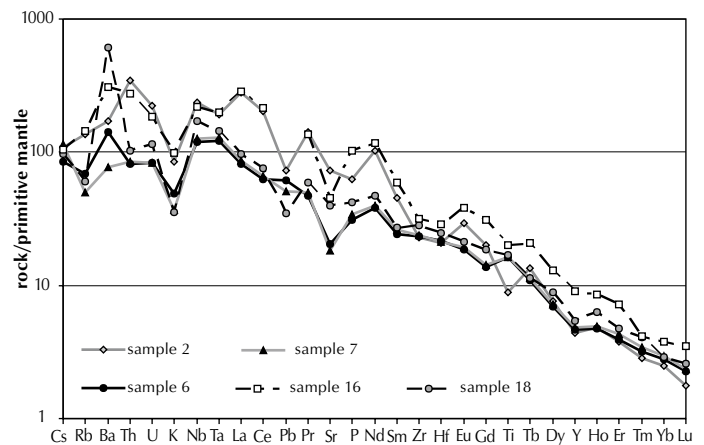
concentrations likely do not have major genetic implications. The lamprophyres are characterized by a positive Ta-Nb ± Ti anomaly. Like many of the rocks hosted by the northern Cordilleran miogeocline, the Quartet Mountain lamprophyres show  $Nb/Y > 1$  (Fig. 10),  $Zr/Nb < 6$  and  $Ce/Y > 2$ . The Neoproterozoic volcanic rocks of Yukon are characterized by distinctly lower high field strength element abundances and have significantly lower Nb/Y, Zr/Y, Nb/Zr and Ce/Y ratios. Ni and Cr concentrations of 774 and 1220 ppm, respectively, in sample 2 probably reflect the abundance of mantle xenoliths in this sample. The xenolith-free samples have Ni and Cr concentrations between 412 and 591 ppm and 364 and 851 ppm, respectively.



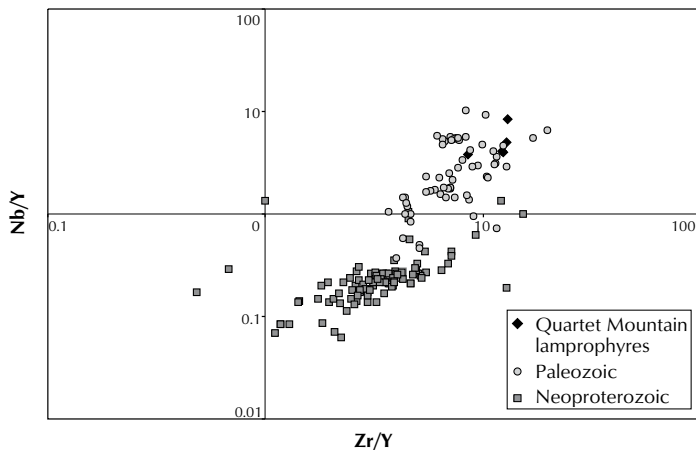
**Figure 8.** Classification diagram for ultramafic lamprophyres and kimberlites. Quartet Mountain lamprophyres plot in the ultramafic lamprophyre field. Modified from Rock (1991).



**Figure 7.** Classification diagram for ultramafic (UML) and alkaline (AL) lamprophyre types showing ultramafic composition of Quartet Mountain lamprophyres (from Rock, 1987).



**Figure 9.** Trace element profiles of Quartet Mountain lamprophyres, normalized to primitive mantle values of Sun and McDonough (1989).



**Figure 10.** Nb/Y vs. Zr/Y diagram comparing Neoproterozoic and Paleozoic igneous rocks in Mackenzie Platform and Selwyn Basin. Data is from Godwin and Price, 1986; Roots, 1988; Goodfellow et al., 1995; Abbott, 1997; Dudas and Lustwerk, 1997; Mustard and Roots, 1997.

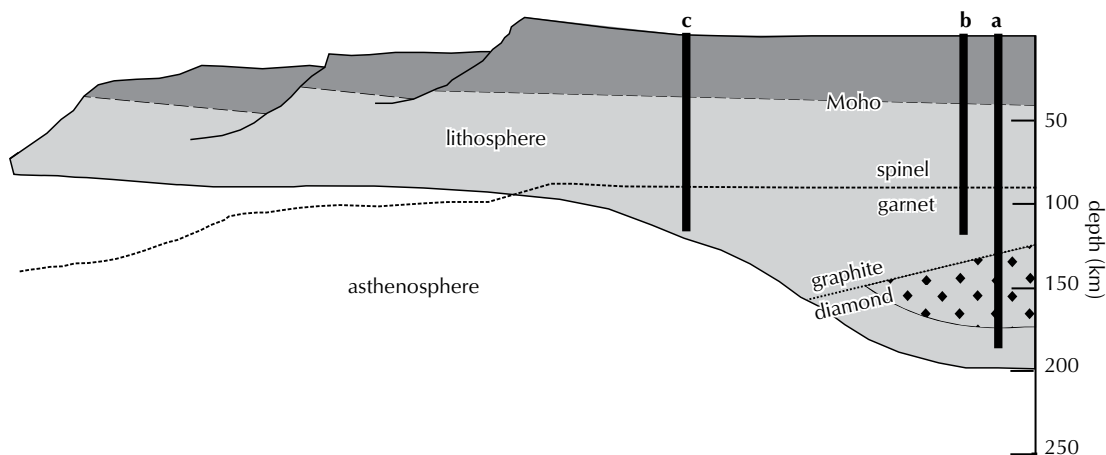
Rare earth element (REE) concentrations suggest the lamprophyres are strongly fractionated (Fig. 9). Chondrite-normalized (Sun and McDonough, 1989) La values range from 236-821 and Lu values range from 5.2-10.2, suggesting an origin as low-degree partial melts. Sample 2 has the highest LREE and the lowest HREE concentrations, and the most fractionated pattern. Samples 6, 7 and 18 show nearly identical REE patterns and very similar overall trace element distributions. Sample 16 shows a significant LREE enrichment relative to samples 6, 7, and 18. Although it is probable that some of the trace element differences are due to variable post-emplacment processes, it is possible that samples 2 and 16 represent smaller degree partial melts derived from the same source as samples 6, 7, and 18. Alternatively, these samples may have originated as partial melts from a different mantle source.

## GEOLOGICAL SIGNIFICANCE

The preliminary Ar-Ar phlogopite dates of ca. 522 Ma (Thorkelson, 2000; Thorkelson et al., 2003) and ca. 532 Ma (Ullrich, pers. comm.) suggest an Early Cambrian emplacement age for the Quartet Mountain ultramafic lamprophyres. Ultramafic lamprophyres are typically emplaced in divergent margin and intraplate tectonic settings (Rock, 1991), and hence fit the general tectonic model of passive margin subsidence punctuated by episodic extensional events for the

northern Cordilleran miogeocline (Gordey and Anderson, 1993; Goodfellow et al., 1995). Numerous, small volume, alkalic, volcanic rocks that have been interpreted as extension related (Roots, 1988; Pell, 1994; Goodfellow et al., 1995) occur along the length of the miogeocline, ranging in age from Cambrian to Devonian. Their alkaline character, timing of emplacement and immobile element ratios are broadly similar to those of the Quartet Mountain lamprophyres, although a petrogenetic link has not been established. Paleozoic kimberlite magmatism in the Slave craton includes the 523-535 Ma Snap Lake dyke (Heaman et al., 2004), which is coeval with the Quartet Mountain lamprophyres. Geological controls on the emplacement of the Slave kimberlites are poorly understood, but they are not thought to be related to the extensional tectonism that affected the northern Cordilleran miogeocline.

The mantle origin of the Quartet Mountain lamprophyres, their ultramafic character, the kimberlitic affinity of sample 2, and the proximity of the Quartet Mountain lamprophyres to the microdiamond-bearing Mountain diatreme command the assessment of the lamprophyres' diamond potential. Diamond-bearing occurrences of ultramafic lamprophyres exist in Canada (e.g., Ile Bizard, Torngat; Rock, 1991; Kjarsgaard and Levinson, 2002) but, together with Type II kimberlites and lamproites, they account for only a small percentage (~8%) of the world's total diamond production. Type I kimberlites, and marine and alluvial sediments are the dominant sources of world's diamond supply (Willmott, 2004). For the lamprophyres to be diamondiferous they must have been generated at depths of at least 140 km from a Cambrian lithospheric mantle root under appropriate physical and geochemical conditions. The garnet-bearing mantle xenoliths in sample 2 constrain the depth of origin of that lamprophyre to at least 90 km (Fig. 11). Factors influencing the suitability of the mantle root include its age, composition, thickness, oxygen fugacity, geothermal gradient and metasomatic history (Haggerty, 1986; Helmstaedt and Gurney, 1995). These factors are presently undetermined for the mantle beneath Yukon in the Cambrian. Based on the interpreted tectonic history of the region, the likelihood of diamondiferous mantle beneath northern Yukon during the Cambrian is modest. Neoproterozoic to Cambrian rifting is likely to have modified the existing mantle root, making it thinner, warmer and less likely to retain a keel of diamond-bearing peridotite and eclogite. Further work is required to more closely ascertain the diamond potential of the lamprophyres.



**Figure 11.** A conceptual cross-section of the crust and upper mantle across the northwestern margin of Early Paleozoic North America. The “diamond window” is illustrated by black diamonds and indicates the area of lithosphere in which diamonds are stable (below approximately 140 km and between 900-1200°C). Conduit **a** illustrates the generation depth and tectonic setting that favours diamond entrainment. Conduit **b** illustrates the source region in a favourable setting, but at a depth that is too shallow for diamond entrainment. The source region of conduit **c** illustrates an unfavourable tectonic setting in which attenuation of the continental lithosphere caused complete disappearance of the potentially diamondiferous mantle root. Which conduit most accurately represents the Quartet Mountain lamprophyres is uncertain.

## CONCLUSIONS

The Quartet Mountain lamprophyres in the study area are phlogopite- ± diopside- ± olivine-phyric dykes that are exposed over a 40 km by 35 km area in the Wernecke Mountains. The lamprophyres crosscut the Paleoproterozoic and Mesoproterozoic strata of the Wernecke and Mackenzie mountains supergroups. Preliminary Ar-Ar dates from phlogopite of ca. 522 Ma (Thorkelson *et al.*, 2003) and ca. 532 Ma (T. Ullrich, pers. comm.) suggest an Early Cambrian age.

Trace element compositions suggest that the lamprophyres were derived by small degrees of partial melting of a parent mantle source. Major and trace element geochemistry, in addition to the limited petrographic information, is consistent with the classification of the Quartet Mountain lamprophyres as ultramafic lamprophyres.

Sample 2 contains mantle and crustal xenoliths, large anhedral to euhedral minerals collectively termed macrocrysts and groundmass. The inequigranular texture of sample 2 is similar to that of kimberlite, but this rock is best classified as ultramafic lamprophyre, based on petrographic and geochemical criteria. A detailed study of the xenoliths is in progress and may yield important

information about the lithospheric architecture of Early Cambrian northwestern North America.

The diamond potential of the Quartet Mountain lamprophyres is modest. The current models for the Early Paleozoic evolution of North America do not favour the presence of a widespread “diamond window” in the lithospheric mantle beneath the Cordillera. However, the nature of the mantle beneath the Mackenzie platform, which hosts the lamprophyres and has undergone less extension than neighbouring regions such as the Selwyn Basin, has not been thoroughly investigated.

## ACKNOWLEDGMENTS

Funding was provided by the Yukon Geological Survey, an NSERC grant to D. Thorkelson, and a Northern Studies Training Program grant to D. Milidragovic. We thank Tom Ullrich from the Pacific Centre for Geochemical and Isotopic Research for the preliminary Ar-Ar phlogopite date from lamprophyre DT-02-12-1-4, Maya Kopylova for allowing access to her kimberlite and lamprophyre collection, and Ryan Ickert for field assistance. Comments by critical readers Dan Gibson and Geoff Bradshaw led to significant improvements.

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