PETROLOGY AND STRATIGRAPHIC SETTING OF THE KAMLOOPS LAKE PICRITIC BASALTS, QUESNELLIA TERRANE, SOUTH-CENTRAL B.C. (92I/9, 15, 16)

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INTRODUCTION

Picritic basalt is exposed in the Intermontane Belt in the southern part of the Quesnellia Terrane, south-central British Columbia (Figure 1). It is found in four localities in the Kamloops Lake area (Figure 2): as small pods within the Early Jurassic Iron Mask batholith; on an isolated knoll near Jacko Lake *just outside the southwestern margin of the Iron Mask batholith; near Carabine Creek on the* north side of Kamloops Lake; and north of Pass Lake near Watching Creek. These rocks are olivine±clinopyroxene-porphyritic, occasionally serpentinized and exhibit volcanic textures. They contain extremely high MgO, anomolously low Al_2O_3, low TiO_2 and are enriched in chromium and nickel.

We present petrographic and chemical data on the Kamloops Lake picritic basalts as well as the stratigraphic setting for these ultramafic lavas. Age constraints derive from field relationships. Mineral chemistry indicates that these ultramafic rocks represent mantle-derived material which has undergone minimal differentiation or crustal contamination and, based primarily on regional geology and whole-rock and mineral chemistry, they represent ultramafic magmatism in an island arc setting. Comparisons to other ultramafic rock suites provide a framework for further interpretation of these rocks.
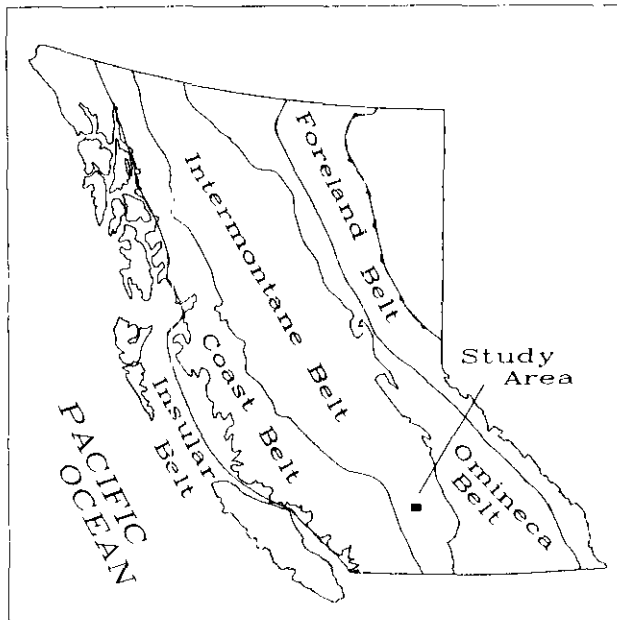
REGIONAL GEOLOGY

The majority of the rocks exposed within the study area are Nicola Group (Figure 2), an extensive sequence of Late Triassic volcanic, volcaniclastic and sedimentary rocks (Preto, 1979). In the Kamloops Lake area, Nicola Group consists mainly of abundant green and red augite porphyry flows and related breccias, bedded and massive tuffaceous siltstones, and minor cherty sediments. Nicola Group rocks have an alkaline chemical signature and characteristically exhibit low-grade greenschist metamorphism (Preto, 1979). The rocks are generally broadly folded, cut by prominent northwest-trending structures, and show a weak foliation.

Intruding and overlying the Nicola Group rocks are a variety of younger intrusive and volcanic rocks, including the Iron Mask batholith and the Kamloops Group. The Iron

Figure 1. Map showing the location of the Kamloops Lake picritic basalts in the southern Intermontane Belt, British Columbia.
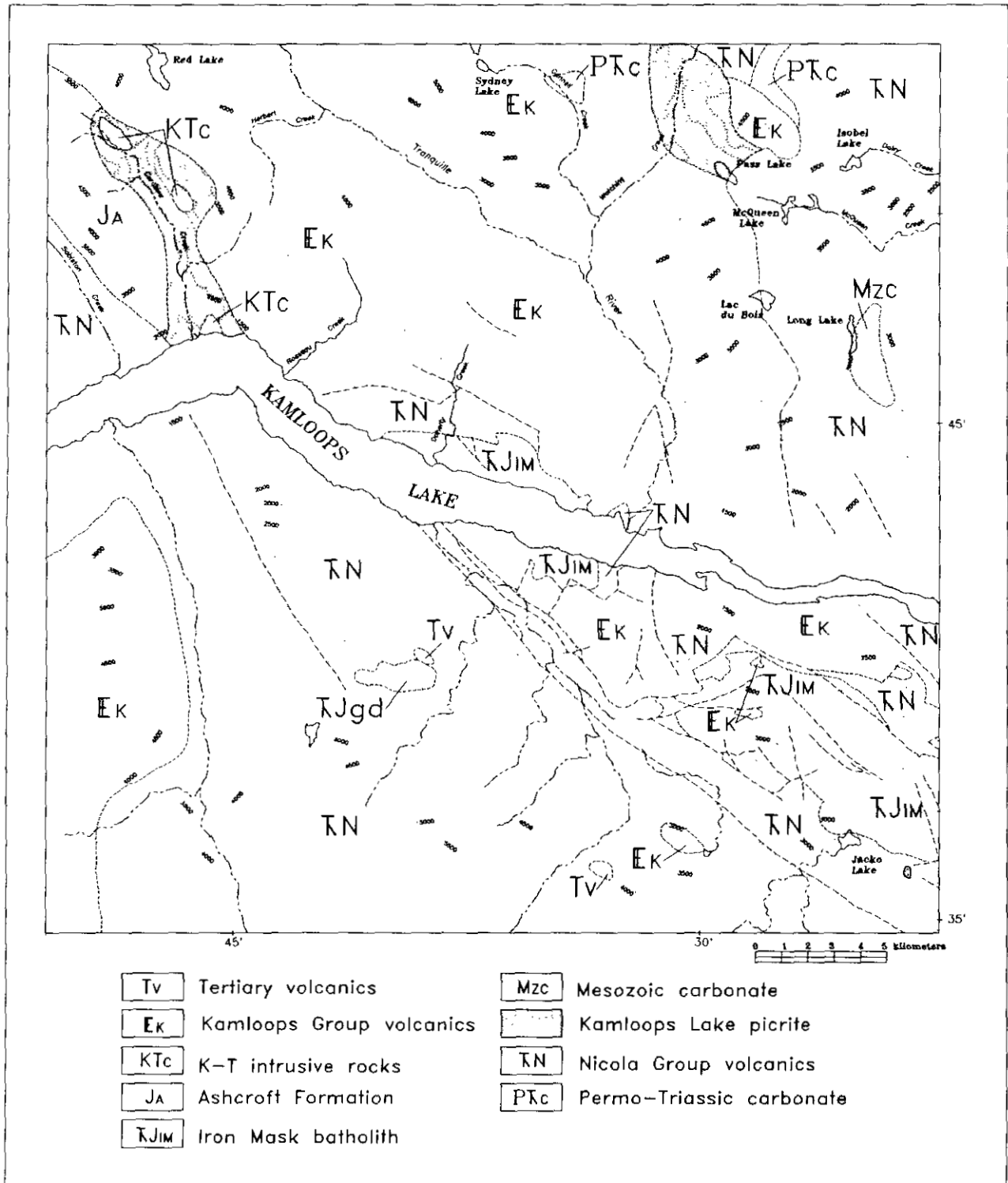
Figure 2. Geology of the Kamloops area. Nicola Group volcanic and sedimentary rocks underlie most of the map area. Picrite occurrences are shown in the stippled pattern.

Mask batholith, a northwesterly trending Early Jurassic composite alkaline intrusive complex, is exposed in the southeast part of the study area (Preto, 1968; Northcote, 1977; Kwong, 1987; Snyder and Russell, 1993). It is intruded along deep-seated structures and contains numerous xenoliths of serpentinized picritic basalt. The Eocene Kamloops Group volcanic rocks overlie much of the study area and consist of abundant alkali basalt flows and minor sedimentary rocks (Ewing, 1982).

Picritic basalt occurs as small, poorly exposed, disconnected bodies in the vicinity of Kamloops Lake. The four locations described in this work are referred to as the Carabine Creek, Watching Creek, Jacko Lake and Iron Mask localities.

HISTORICAL PERSPECTIVES AND PREVIOUS WORK

Mathews (1941) and Cockfield (1948) described two occurrences of picritic basalt exposed on the north side of Kamloops Lake near Watching Creek and Carabine Creek, assigning them to a Cretaceous or Tertiary package of volcanic rocks. They described the rocks as "effusive" and characterized by "vitreous bases". Mathews also identified similar rocks within the Iron Mask batholith and the presence of a small area of "peridotite" near Jacko Lake. The latter was presumed to be a small intrusion unrelated to either the Nicola Group or the batholith.

Carr (1957) noted that the picritic basalt in the Iron Mask batholith occurs as small, lenticular serpentinized bodies, commonly associated with northwest-trending structures. He interpreted the serpentinites as non-batholithic, post-Nicola intrusions. Carr also suggested that the unaltered "peridotite" near Jacko Lake is similar to picritic basalt north of Kamloops Lake. Some of the outcrops he included as basalt are, in fact, augite porphyries of the Nicola Group. Preto (1968) suggested that the picritic basalt in the Iron Mask batholith was pre-Kamloops Group (Eocene) and noted the presence of dioritic dikes which crosscut outcrops of serpentinite; Northcote (1977) assigns the dikes to late-stage phases of the Iron Mask intrusive suite.

Snyder and Russell (1993) reinterpreted the relative age relationships of the phases of the Iron Mask batholith and concluded that the picritic basalt is pre-Iron Mask in age. They suggest that serpentinization of the basalts resulted from interaction with the batholith

during emplacement. They also note the textural and mineralogical similarity in rocks from the four localities in the Kamloops Lake area. Ross et al. (1993) report that although lenses of picritic basalt are commonly associated with mineralized zones such as the Afton orebody on the northern margin and the Ajax properties near the southwest margin of the batholith, they are not mineralized.

FIELD AND STRATIGRAPHIC RELATIONSHIPS

Picritic basalt crops out near Jacko Lake, approximately 1 kilometre from the southwest margin of the Iron Mask batholith on a small, isolated knoll. A distinctive feature of this locality is the presence of rounded aggregates of olivine and clinopyroxene ranging from 1 to 20 centimetres in diameter. The mineral grains in the aggregates are the equivalent size of the crystals in the groundmass. Outcrops have a subtle layering defined by the proportion of these aggregates. Basalt at Jacko Lake is cut by a small (0.6 m wide) felsic dike which is inferred to be a late phase of the Iron Mask batholith.

The picritic basalt exposed at Carabine Creek on the north side of Kamloops Lake is similar in appearance to the Jacko Lake outcrop but there is greater exposure. Although olivine and clinopyroxene aggregates are present, they are not as abundant. The basalt at Carabine Creek is intruded by small stocks of granitic composition belonging to the post-Early Cretaceous Copper Creek Plutonic Suite (Cockfield, 1948).

Ultramafic rocks at the Watching Creek locality, north of Pass Lake, are massive; the outcrops are typically dense, black and structureless. The rocks contain more olivine phenocrysts (up to 50%) than observed at the other localities and are weakly porphyritic. Aggregates of olivine and clinopyroxene were not seen at Watching Creek, but hematite is ubiquitous at this locality, giving some samples a reddish colour.

Picritic basalt occurs in the Iron Mask batholith as small, serpentinized xenoliths and septa. Olivine is generally the only primary mineral preserved, although clinopyroxene is locally present. Serpentine, replacing original minerals, commonly preserves fragmental textures. Contacts with Iron Mask units or Nicola Group rocks are generally sheared; one contact seen in drill core from near Jacko Lake

(Figure 2) is unsheared and shows the basalt in sharp contact with Nicola augite porphyry.

Picritic basalt at the Jacko Lake locality overlies Nicola volcanic rocks, indicating that it is younger than the Late Triassic. Because picritic basalt is found as xenoliths within the Early Jurassic (207±3 Ma, Ghosh, 1993) Iron Mask batholith, the ultramafic magmatism is definitively older. At Carabine Creek, the picritic basalt is overlain by Kamloops Group volcanic rocks, supporting a pre-Eocene age for the basalts. These relationships constrain the age of the Kamloops Lake suite to the latest Triassic or earliest Jurassic.

PETROGRAPHY

Picritic basalts in the Kamloops Lake area are olivine±clinopyroxene-porphyritic. Spinel occurs ubiquitously as microphenocrysts, inclusions in olivine and clinopyroxene, and in the groundmass. The groundmass is typically fine grained and altered to either serpentine or

TABLE 1. REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF OLIVINE PHENOCRYSTS IN THE KAMLOOPS LAKE PICRITIC BASALTS.

	Carabine Creek				Watching Creek			
Sample	224	224	225	225	240	240	241	241
Position	C	R	I	R	C	R	C	R
SiO_2	41.24	41.16	40.83	40.39	39.95	39.66	40.03	40.04
Al_2O_3	0.04	b.d.	0.04	0.05	0.05	0.02	b.d.	0.04
Cr_2O_3	0.08	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
FeO	6.96	7.66	9.03	8.88	10.07	10.10	10.33	10.07
MnO	0.12	0.17	0.18	0.13	0.24	0.22	0.18	0.24
MgO	51.25	50.94	49.39	49.19	48.67	48.43	48.82	48.91
CaO	0.05	0.06	0.38	0.42	0.28	0.28	0.26	0.25
NiO	0.43	0.33	0.22	0.32	0.30	0.31	0.28	0.33
TOTAL	100.17	100.32	100.07	99.38	99.56	99.02	99.90	99.88
Atoms/4(O)								
Si	0.997	0.997	0.998	0.995	0.988	0.987	0.988	0.987
Al	0.001	0.000	0.001	0.001	0.001	0.001	0.000	0.001
Cr	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fe^{2+}	0.141	0.155	0.185	0.183	0.208	0.210	0.213	0.208
Mn	0.002	0.003	0.004	0.003	0.005	0.005	0.004	0.005
Mg	1.848	1.840	1.800	1.806	1.795	1.797	1.796	1.798
Ca	0.001	0.002	0.010	0.011	0.007	0.007	0.007	0.007
Ni	0.008	0.006	0.004	0.006	0.006	0.006	0.006	0.007
Fo%	92.4	91.9	90	90.2	89.7	89.9	89.8	89.9
	Jacko Lake				Iron Mask			
Sample	230	230	99	99	07	07	07	07
Position	R	C	R	I	C	R	I	R
SiO_2	40.80	40.91	40.60	40.74	40.92	40.80	40.79	40.91
Al_2O_3	0.04	b.d.	0.05	0.03	0.04	0.02	0.05	0.05
Cr_2O_3	b.d.	b.d.	b.d.	b.d.	0.11	b.d.	b.d.	0.08
FeO	7.63	7.66	8.84	8.98	7.73	8.92	7.81	7.69
MnO	0.11	0.08	0.19	0.17	0.08	0.17	0.13	0.10
MgO	50.40	50.22	50.31	49.96	51.37	50.07	51.26	51.71
CaO	0.08	0.07	0.29	0.23	0.09	0.18	0.09	0.11
NiO	0.41	0.39	0.32	0.34	0.42	0.31	0.28	0.39
TOTAL	99.47	99.33	100.60	100.45	100.76	100.47	100.41	101.04
Atoms/4(O)								
Si	0.997	1.001	0.988	0.992	0.988	0.993	0.989	0.986
Al	0.001	0.000	0.001	0.001	0.001	0.001	0.001	0.001
Cr	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.002
Fe^{2+}	0.156	0.157	0.180	0.183	0.156	0.182	0.158	0.155
Mn	0.002	0.002	0.004	0.004	0.002	0.004	0.003	0.002
Mg	1.836	1.831	1.825	1.815	1.850	1.817	1.852	1.857
Ca	0.002	0.002	0.008	0.006	0.002	0.005	0.002	0.003
Ni	0.008	0.008	0.006	0.007	0.008	0.006	0.005	0.008
Fo%	91.8	91.5	91.2	90.7	92.5	90.8	92.6	92.9

Sample numbers refer to whole-rock analyses in Table 4. Formulae calculated on 4 oxygens; C=core, I=interior, R=rim.

talc. The basalts can be subdivided texturally into cumulate and volcanic rocks. The Watching Creek locality typifies the cumulate phase; olivine phenocrysts occur in a groundmass of intercumulus clinopyroxene phenocrysts. Rocks from the three other localities are characterized by a volcanic texture, with olivine phenocrysts and smaller, euhedral clinopyroxene microphenocrysts in a fine-grained groundmass. At Carabine Creek, numerous small (< 0.2 cm) vesicles are filled with secondary fibrous thomsonite, a variety of zeolite.

Olivine phenocrysts are subhedral to euhedral and range in size from 0.5 to 3.5 millimetres. The grains show no resorption features and are generally altered only slightly at the rims and along fractures in the mineral grains. Olivine phenocryst abundances in the Kamloops Lake picritic basalts range from 20 to 30% at Iron Mask, Jacko Lake and Carabine Creek and 35 to 50% at Watching Creek. Anhedral inclusions of spinel within olivine grains are common in most samples. In the most altered rocks, olivine phenocrysts are rimmed by anhedral, fine-grained opaque material interpreted as secondary spinel produced through the breakdown of olivine.

Clinopyroxene occurs as anhedral phenocrysts (Watching Creek), and subhedral to euhedral microphenocrysts (Carabine Creek, Jacko Lake, Iron Mask). Clinopyroxene represents approximately 20 to 25% (Watching Creek) to 30 to 45% (Jacko Lake, Carabine Creek) of the rock and ranges in size from 0.05 to 0.25 millimetre (Jacko Lake, Carabine Creek) or 0.5 to 2.5 millimetres (Watching Creek). Grains generally exhibit a slight yellowish pleochroism and inclusions of subhedral to anhedral spinel in both forms of clinopyroxene are very common, indicating that olivine and spinel were the primary liquidus phases. Zoning is evident only in the microphenocrysts in the non-cumulate rocks. Pigeonite has been reported at the Jacko Lake locality by Mathews (1941), but none was recognized during this study.

Spinels in the picritic basalts occur throughout the crystallization sequence; small inclusions of subhedral to anhedral spinel within olivine and clinopyroxene are common. Spinel also occurs as subhedral to anhedral microphenocrysts up to 0.3 millimetre and is scattered throughout the groundmass in crystals ranging from 0.005 to 0.15 millimetre across. Serpentinized picritic basalt in the Iron Mask batholith has oxides as an alteration product through the breakdown of olivine and clinopyroxene to serpentine, talc and tremolite during hydrothermal alteration induced by the

Iron Mask intrusive suite. The majority of spinels from these samples are not primary and are not included in the following discussion of mineral compositions.

MINERAL CHEMISTRY

The three major phases, olivine, clinopyroxene and spinel were analyzed on a Cameca SX-50 electron microprobe at The University of British Columbia, with operating conditions of 15 kilovolts and 20 or 30 nanoamps.

Representative olivine compositions for each of the four Kamloops Lake picritic basalt localities are shown in Table 1. Compositions of olivine phenocrysts range from $Fo_{92.9-89.5}$, reflecting the high magnesium content of the magma. Zoning in the olivine phenocrysts ranges from unzoned in the Watching Creek locality to slightly zoned (up to 1 mole % Fo from core to rim) at the Carabine Creek, Jacko Lake and Iron Mask localities.

The NiO content in the olivine phenocrysts from the Kamloops Lake suite ranges from 0.22 to 0.43 weight% but is not correlated to forsterite content (Figure 3). In contrast, data from some other ultramafic rock suites exhibits a well-defined positive trend of forsterite content versus NiO (Gorgona Island; Echeverria, 1980; Kilauea picritic basalts; Nicholls and Stout, 1988). Furthermore, NiO contents of olivine are slightly greater for a similar forsterite composition in these suites. Olivines from
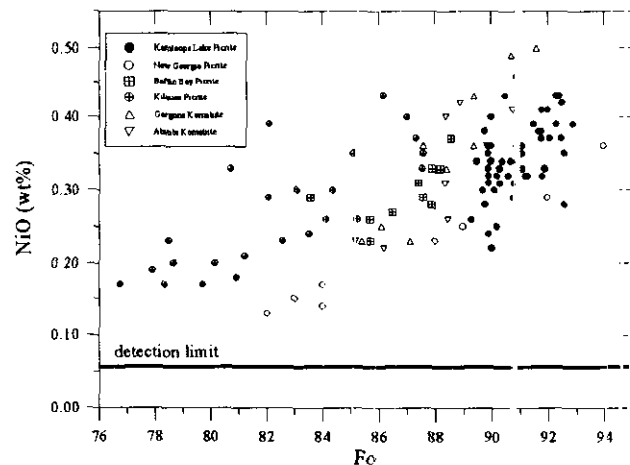

Figure 3. Forsterite content vs nickel (ppm) for olivine from the Kamloops Lake picrites and other ultramafic suites. Sources of data: New Georgia (Ramsay et al., 1984), Baffin Bay (Francis, 1985), Kilauea (Nicholls and Stout, 1988), Gorgona (Echeverria, 1980) and Abitibi (Barnes et al., 1980).

TABLE 2. REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF CLINOPYROXENE PHENOCRYSTS AND MICROPHENOCRYSTS IN THE KAMLOOPS LAKE PICRITIC BASALTS.

	Carabine Creek				Watching Creek			
Sample	224	224	225	225	240	240	241	241
Position	mp-C	mp-I	mp-C	mp-I	pheno-C	pheno-R	pheno-C	pheno-I
SiO_2	51.80	50.84	52.01	52.95	51.17	51.15	51.72	49.32
TiO_2	0.16	0.25	0.18	0.15	0.20	0.28	0.15	0.41
Al_2O_3	2.54	3.26	2.46	1.62	2.97	3.01	2.22	4.32
Cr_2O_3	0.94	0.62	0.92	0.85	0.69	0.51	0.77	0.43
FeT	4.65	5.39	4.23	3.50	4.98	5.01	4.27	6.02
MnO	0.09	0.12	0.06	0.09	0.07	0.07	b.d.	0.12
MgO	16.80	16.05	16.79	17.34	16.55	16.51	17.20	15.64
CaO	22.26	22.38	22.52	22.44	22.53	22.40	22.63	22.72
Na_2O	0.26	0.28	0.25	0.23	0.29	0.29	0.28	0.27
NiO	b.d.	0.07	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
TOTAL	99.50	99.26	99.42	99.17	99.45	99.23	99.24	99.25
Atoms/6(O)								
Si	1.901	1.875	1.909	1.944	1.879	1.882	1.897	1.820
Ti^{4+}	0.004	0.007	0.005	0.004	0.006	0.008	0.004	0.011
Al	0.099	0.125	0.091	0.056	0.121	0.118	0.096	0.180
Al^{VI}	0.011	0.017	0.015	0.014	0.007	0.012	0.000	0.008
Cr^{3+}	0.027	0.018	0.027	0.025	0.020	0.015	0.022	0.013
Fe^{3+}	0.070	0.096	0.056	0.025	0.103	0.095	0.098	0.154
Fe^{2+}	0.072	0.070	0.073	0.082	0.050	0.059	0.033	0.031
Mn	0.003	0.004	0.002	0.003	0.002	0.002	0.000	0.004
Mg	0.919	0.882	0.919	0.949	0.906	0.906	0.941	0.861
Ca	0.875	0.884	0.886	0.882	0.886	0.883	0.889	0.898
Na	0.018	0.020	0.018	0.016	0.021	0.021	0.020	0.019
Ni	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000
MG#	92.73	92.65	92.64	92.05	94.77	93.89	96.61	96.52

	Jacko Lake				Iron Mask			
Sample	230	230	99	99	07	07	07	07
Position	mp	mp	mp-C	mp-I	mp-C	mp-I	mp-I	mp-I
SiO_2	51.07	51.14	51.24	51.98	50.84	52.57	51.52	51.67
TiO_2	0.25	0.25	0.19	0.17	0.20	0.14	0.19	0.17
Al_2O_3	2.96	2.89	2.79	2.21	3.32	1.94	2.73	2.41
Cr_2O_3	0.26	0.26	0.83	0.78	0.98	0.80	0.87	0.80
FeT	5.32	5.87	4.71	4.26	4.75	3.93	4.32	4.22
MnO	b.d.	0.14	0.10	0.12	0.08	0.07	0.08	0.08
MgO	16.51	16.38	16.74	17.40	16.82	17.98	17.32	17.69
CaO	22.17	21.99	22.48	22.35	21.94	21.88	22.34	22.10
Na_2O	0.24	0.31	0.28	0.28	0.24	0.22	0.22	0.22
NiO	b.d.	b.d.	b.d.	b.d.	b.d.	0.07	b.d.	b.d.
TOTAL	98.78	99.23	99.36	99.55	99.17	99.60	99.59	99.36
Atoms/6(O)								
Si	1.888	1.885	1.882	1.900	1.870	1.918	1.883	1.890
Ti^{4+}	0.007	0.007	0.005	0.005	0.006	0.004	0.005	0.005
Al	0.112	0.115	0.121	0.095	0.130	0.082	0.117	0.104
Al^{VI}	0.017	0.011	0.003	0.000	0.014	0.001	0.001	0.000
Cr^{3+}	0.008	0.008	0.024	0.023	0.028	0.023	0.025	0.023
Fe^{3+}	0.091	0.105	0.100	0.091	0.093	0.066	0.095	0.098
Fe^{2+}	0.074	0.076	0.044	0.039	0.053	0.054	0.037	0.031
Mn	0.000	0.004	0.003	0.004	0.002	0.002	0.002	0.002
Mg	0.910	0.900	0.917	0.948	0.922	0.978	0.944	0.965
Ca	0.878	0.868	0.885	0.875	0.865	0.855	0.875	0.866
Na	0.017	0.022	0.020	0.020	0.017	0.016	0.016	0.016
Ni	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000
MG#	92.48	92.21	95.42	96.05	94.56	94.77	96.23	96.89

MG# = 100*Mg/(Mg+Fe^{2+}). Sample numbers refer to whole-rock analyses in Table 4.
Formulae calculted on 6 oxygens; P=phenocryst, MP=microphenocryst, C=core,
I=interior, R=rim.

TABLE 3. REPRESENTATIVE ELECTRON MICROPROBE ANALYSES OF SPINEL IN THE KAMLOOPS LAKE PICRITIC BASALTS.

	Carabine Creek				Watching Creek			
Sample	224	224	225	225	240	240	240	240
Position	gm	inc-ol	inc-py-C	inc-ol-C	pheno-R	pheno-C	inc-py-I	inc-py-I
SiO_2	0.15	0.06	0.06	0.03	0.04	0.06	0.07	0.04
TiO_2	0.60	0.40	0.58	0.58	1.43	1.16	1.22	1.03
Al_2O_3	8.83	7.17	8.53	8.30	12.08	9.25	8.62	8.63
Cr_2O_3	28.70	49.46	30.60	27.92	10.82	13.65	16.04	15.81
Fe_2O_3	16.00	14.56	15.06	15.57	20.32	19.02	18.62	18.41
FeO	33.22	14.63	32.36	35.32	45.45	46.67	45.31	45.77
MnO	0.43	0.10	0.16	0.21	0.26	0.20	0.23	0.22
MgO	10.83	11.74	11.54	11.21	8.83	9.31	9.58	9.52
CaO	0.09	0.03	0.13	b.d.	0.03	b.d.	0.02	0.02
NiO	0.25	0.17	0.28	0.30	0.40	0.39	0.39	0.41
ZnO	0.09	0.10	b.d.	b.d.	b.d.	b.d.	0.09	0.08
TOTAL	99.19	98.43	99.30	99.44	99.66	99.71	100.19	99.94
Atoms/32(O)								
Si	0.040	0.016	0.016	0.008	0.011	0.016	0.019	0.011
Ti^{4+}	0.122	0.081	0.117	0.118	0.291	0.238	0.249	0.211
Al	2.808	2.280	2.699	2.636	3.846	2.972	2.759	2.770
Cr^{3+}	6.123	10.553	6.496	5.950	2.311	2.943	3.444	3.405
Fe^{3+}	6.745	2.971	6.539	7.163	9.240	9.576	9.260	9.381
Fe^{2+}	3.610	3.287	3.380	3.509	4.590	4.338	4.228	4.194
Mn^{2+}	0.098	0.023	0.036	0.048	0.059	0.046	0.053	0.051
Mg	4.357	4.723	4.619	4.504	3.556	3.785	3.879	3.866
Ca	0.026	0.009	0.037	0.000	0.009	0.000	0.006	0.006
Ni	0.054	0.037	0.060	0.065	0.087	0.086	0.085	0.090
Zn	0.018	0.020	0.000	0.000	0.000	0.000	0.018	0.016
CR#	68.56	82.23	70.65	69.30	37.53	49.75	55.52	55.14
MG#	54.69	58.96	57.74	56.21	43.65	46.60	47.35	47.97

	Jacko Lake					
Sample	230	230	230	230	99	99
Position	pheno-C	pheno-I	gm	gm	inc-py-I	inc-py
SiO_2	0.03	0.05	0.56	0.92	0.06	0.74
TiO_2	0.48	0.56	0.40	0.72	0.55	0.51
Al_2O_3	8.10	8.56	7.16	9.02	7.63	6.94
Cr_2O_3	33.75	30.50	32.93	22.45	26.09	27.10
Fe_2O_3	14.43	14.95	18.73	19.52	14.88	15.20
FeO	30.89	33.91	30.56	37.08	38.34	36.08
MnO	0.15	0.17	0.23	0.24	0.20	0.16
MgO	12.10	12.03	9.60	9.53	11.50	11.64
CaO	b.d.	b.d.	0.04	0.08	0.17	0.14
NiO	0.29	0.28	0.24	0.31	0.31	0.34
ZnO	0.08	b.d.	0.07	b.d.	b.d.	b.d.
TOTAL	100.29	101.01	100.52	99.86	99.73	98.85
Atoms/32(O)						
Si	0.008	0.013	0.151	0.249	0.016	0.201
Ti^{4+}	0.096	0.111	0.081	0.146	0.111	0.104
Al	2.535	2.661	2.281	2.873	2.421	2.218
Cr^{3+}	7.086	6.361	7.038	4.797	5.555	5.810
Fe^{3+}	6.172	6.730	6.216	7.540	7.769	7.362
Fe^{2+}	3.203	3.297	4.234	4.410	3.350	3.448
Mn^{2+}	0.034	0.038	0.053	0.055	0.046	0.037
Mg	4.790	4.731	3.869	3.840	4.617	4.706
Ca	0.000	0.000	0.012	0.023	0.049	0.041
Ni	0.062	0.059	0.052	0.067	0.067	0.074
Zn	0.016	0.000	0.014	0.000	0.000	0.000
CR#	73.65	70.51	75.52	62.54	69.65	72.37
MG#	59.93	58.93	47.75	46.55	57.95	57.71

CR# = 100*Cr/(Cr+Al); MG# = 100*Mg/(Mg+Fe^{2+}). Sample numbers refer to whole-rock analyses in Table 4. Formulae calculated on 32 oxygens; P=phenocryst, MP=microphenocryst, GM=groundmass, INC=inclusion (host mineral indicated), C=core, I=interior, R=rim.

the New Georgia arc (Ramsay *et al.*, 1984), although also showing a positive correlation between NiO and forsterite content, are, in general, depleted in NiO with respect to the Kamloops Lake picritic basalts. Nickel concentrations and forsterite contents of olivines in Kamloops Lake picrites are consistent with mantle-derived olivine (Sato, 1977). The CaO concentration in olivines from the picritic basalts averages 0.25 weight% which for basaltic rocks would suggest an extrusive or hypabyssal crystallization environment for the magma (Simkin and Smith, 1970).

Analyses of representative clinopyroxene phenocrysts and microphenocrysts for the Kamloops Lake picritic basalts are given in Table 2. Clinopyroxenes are diopsidic in composition with a slightly sub-calcic signature and composition varies little between localities, and between phenocrysts, microphenocrysts or groundmass. Minor zoning is seen in clinopyroxene crystals, with the Watching Creek locality exhibiting minimal normal zoning (core to rim of 5 mol% Mg), while the non-cumulate rocks tend to be more strongly zoned (core to rim up to 16 mol% Mg).The overall range in $100*Mg/(Mg+Fe^{2+})$ is from 87.1 to 99.7, probably indicating that the Mg/Fe ratio in the melt was large or that the oxygen fugacity during clinopyroxene crystallization was quite high. In addition, all clinopyroxenes contain a significant amount of Fe^{3+} (see Table 2), which also suggests that the melt crystallized under high oxygen fugacity (Barsdell, 1988).

Chromium contents in the clinopyroxenes range from below detection limit to 1.32 weight% with an average of 0.66 weight%, consistent with the chromium content of the rocks. No systematic differences with respect to chromium contents are apparent between the cumulate and non-cumulate rocks. The moderate Al_2O_3 contents of the clinopyroxenes (1.63-4.70 wt%) are anomalous compared to the very low whole-rock Al_2O_3 contents, but Al_2O_3, TiO_2 (0.12-0.43 wt%) and Na_2O (0.17-0.33 wt%) contents of the Kamloops Lake picritic basalts are comparable to other island arc picrite suites such as Grenada (Arculus, 1978) and New Georgia (Ramsay *et al.*, 1984). Clinopyroxenes from the komatiite suites of Gorgona Island (Echeverria, 1980) and the Abitibi greenstone belt (Barnes *et al.*, 1983) typically contain more Al_2O_3. Sun and Nesbitt (1979) report that titanium contents in clinopyroxene from island arc suites are typically lower than for oceanic suites.
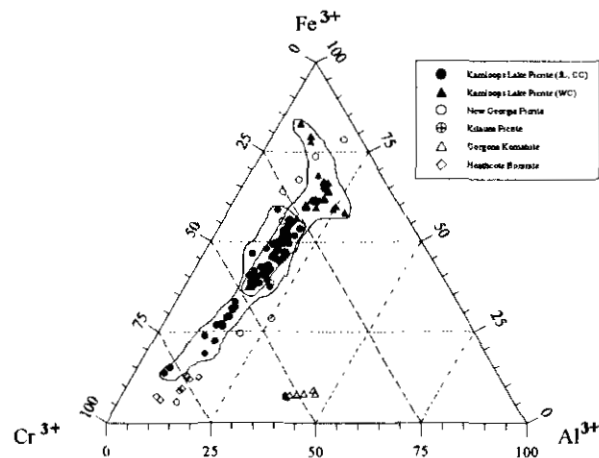

Figure 4. Ternary plot of the proportions of the cations Cr^{3+}, Al^{3+}, and Fe^{3+} in spinels from Kamloops Lake picritic basalts. Fields are indicated for rocks with volcanic (Carabine Creek, Jacko Lake) vs cumulate texture (Watching Creek).

Spinels from the Kamloops Lake picritic basalts exhibit a wide range of chemistry; representative analyses are given in Table 3. Spinels have consistently low Al_2O_3 contents (8.39 wt% average) and variable chromium and iron (Fe^{3+}) contents (Figure 4). Systematic zoning in the spinels is not observed. In general, spinels from cumulate rocks at Watching Creek are higher in iron while spinels from non-cumulate rocks lie on the chromium-rich side of the spectrum. In comparison to the Kamloops Lake picritic basalts, komatiites from Gorgona Island (Echeverria, 1980) have higher Al_2O_3 concentrations, while spinels from other ultramafic suites are comparable to the Kamloops Lake picritic basalts.

Figure 5 shows the range of spinel compositions. Again, the spinel compositions of the Kamloops Lake picritic basalts form two groups representing cumulate *versus* non-cumulate rocks, although there is a continuous spectrum of compositions with no obvious gaps in the spinel solid solution sequence. Spinel compositions from the Kamloops Lake picritic basalts are distinguished from spinels found in komatiites by depleted abundances of ZnO and MnO (Plaksenko and Smol'kin, 1990).

There is a weak correlation in spinels from the Kamloops Lake picritic suite between increasing Cr/(Cr+Al) and increasing $Mg/(Mg+Fe^{2+})$. This trend is similar to spinels from lavas associated with arc magmatism (Ramsay *et al.*, 1984). In addition, the $Fe^{3+}/(Fe^{3+}+Cr+Al)$ ratios in the spinels of the Kamloops Lake picrites are all higher than the
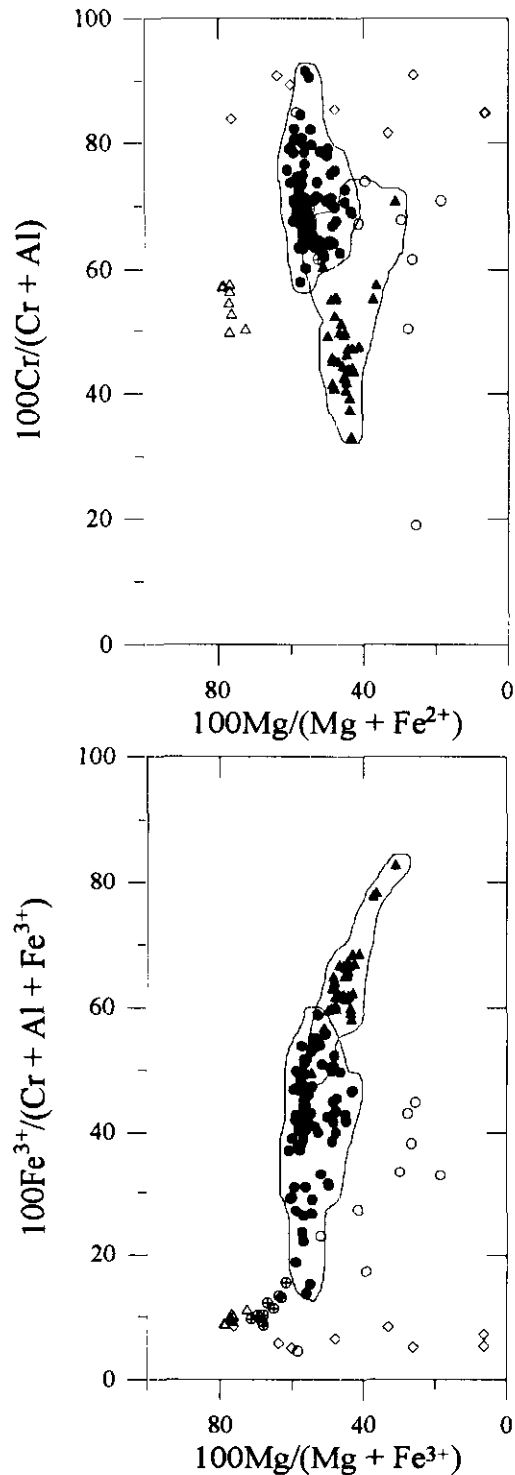
Figure 5. Spinel compositions for Kamloops Lake picritic basalts shown as: (a)Mg/Mg+Fe^{2+} vs Cr/Cr+Al and (b) Mg/(Mg+Fe^{2+}) vs Fe^{3+}/(Fe^{3+}+Cr+Al). Symbols as in Figure 4 represent data from: New Georgia (Ramsay *et al.*, 1984), Kilauea (Nicholls and Stout, 1988), Gorgona (Echeverria, 1980) and Heathcote (Crawford and Cameron, 1985)

highest value of this ratio for the majority of basic rocks (see Figure 5b), illustrating the oxidized nature of these spinels relative to si ites found in other tectonic settings. All other occurrences of strongly oxidized spinels occi r in lavas in an island arc setting (Ramsay *et al.*, 1984; Utter, 1978). In addition, Dick and Bullen (1984) would group spinels with a Cr/Cr+Al ratio similar to that observed in the Kamloof s Lake picritic basalts into spinels derived from island arc sources.

ROCK CHEMISTRY

Whole-rock major and trace element analyses and normative mineralogy for the Kamloops Lake picritic basalts are given in Table 4. These picritic basalts have exceptionally low Al$_2$O$_3$ contents (2.17 to 6.34 wt%), low silica (38.4-43.2 wt%) and very h gh MgO (24.3-33.65 wt%). TiO$_2$ and CaO contents are depleted with respect to some other picritic suites (Deccan, Baffin Bay) possibly due to the very high MgO. The Kamloops Lake picritic basalts also have large concentrations of nickel (920-1420 ppm) and chromium (1670-3040 ppm). The serpentinization of the Iron Mask localities does not significantly alter the rock chemistry.

Figure 6 shows Harker diagrams of MgO, Al$_2$O$_3$ and SiO$_2$ for the Kamloops Lake picritic basalts and several other ultramafic suites. On all diagrams, the Kamloops Lake rocks fall a: extreme ends of the chemical spectrum; they are enriched in MgO and depleted in SiO$_2$ and Al$_2$O$_3$ compared to other ultramafic suites. The extremely high MgO content is unlike many other picritic suites (Ramsay *et al.*, 1984; Krishnamurthy and Cox, 1997) and, taking MgO content alone into consideration, the Kamloops Lake picritic basalts are similar to some komatiite suites (Abitibi greenstone bel, Barberton Mountains). However, the Kamloops Lake magmas are enriched in strontium, barium, nickel and chromium relative to komatiite melts (Plaksenko and Smol'kin, 1990), distinguishing them as true picrites. Boninites contain more SiO$_2$ and less MgO than either komatiites or picrites.

Testing for a cogenetic relationship between the four occurrences of the Kamloops Lake picritic basalts was undertaken using Pearce element-ratio diagrams (Pearce, 1968; Russell and Nicholls, 1988; Nicholls and Russell, 1991). The principal concept behind this method is that rocks that are related to each other through fractionation or accumulation of a given mineral

TABLE 4. WHOLE-ROCK MAJOR AND TRACE ELEMENT CHEMICAL COMPOSITIONS OF THE KAMLOOPS LAKE PICRITIC BASALT WITH CALCULATED NORMATIVE MINERALOGY.

	225 CC	222 CC	241 WC	230 JL	108* IM	309 IM	error
SiO_2	40.40	38.70	38.40	41.30	39.33	43.20	0.197
TiO_2	0.230	0.193	0.166	0.240	0.21	0.386	0.005
Al_2O_3	3.80	3.08	2.17	3.94	2.74	6.84	0.056
Fe_2O_3	2.63	6.42	10.30	4.48	11.00	5.01	0.063
FeO	3.97	2.64	--	4.72	--	4.40	0?
MnO	0.17	0.17	0.18	0.17	0.20	0.14	0.004
MgO	31.40	32.80	32.60	32.30	33.65	24.30	0.217
CaO	4.72	3.20	5.32	4.91	3.53	6.03	0.109
Na_2O	0.09	0.02	0.08	0.18	0.15	0.30	0.012
K_2O	0.95	0.22	0.15	1.50	0.57	2.21	0.012
P_2O_5	0.11	0.10	0.05	0.10	0.06	0.13	0?
H_2O+	7.80	11.10	9.20	4.70	7.38	4.80	
CO_2	0.08	0.08	0.36	0.04	0.08	0.03	
LOI	8.45	11.80	9.75	4.80	7.10	5.00	
SUM	**100.44**	**100.08**	**99.57**	**99.61**	**99.45**	**98.68**	

Trace Elements

Ba[1]	213	147	226	521	129	354	
Rb[2]	31.11		3.83	26.03	16.30		
Sr[2]	216.44		41.00	112.92	14.00		
Nb[2]	0.59		0.13	0.37	0.31		
Zr[2]	11.80		4.35	10.85	10.55		
Y[2]	4.34		2.57	4.03	3.90		
Ni[1]	1350	1380	1420	1410	1254	920	
Cr[1]	2580	3040	2790	2990	2902	1670	
V[2]	110.91		61.90	103.12	74.95		
Sc[2]	18.27		21.41	17.41	20.73		
Th[2]	0.23		0.10	0.27	0.28		
U[2]	0.09		0.06	0.09	0.20		
Pb[2]	1.50		0.99	1.65	0.31		
Hf[2]	0.51		0.16	0.44	0.39		
Cl[1]	128	109	293	125	396	125	
Co[1]	80	85	87	85	92	66	
Cu[1]	25	15	20	30	25	17	
F[1]	75	110	20	90	45	192	
Ga[1]	16	16	16	16	17	19	
S[1]	-50	-50	1120	-50	1662	-50	
Sn[1]	10	10	7	12	4	10	
Ti[1]	1210	981	746	1160	1210	1780	
Zn[1]	58	60	61	60	50	58	
Li[2]	6.57		7.70	6.62	4.69		
Be[2]	0.65		0.01	0.82	0.81		
Mo[2]	0.11		0.47	0.25	3.40		
Cs[2]	0.63		0.24	1.43	0.80		
Ta[2]	0.37		0.08	0.17	0.15		
Tl[2]	0.23		-0.08	0.09	0.09		
Bi[2]	0.07		-0.06	0.17	0.10		

Normative Mineralogy**

OR	6.38	1.50	1.01	6.59	3.74	14.15	
(AL)	0.86	0.19	0.77	0.00	1.40	2.75	
(AN)	8.10	8.82	5.78	6.68	5.66	11.67	
LU	0.00	0.00	0.00	2.30	0.00	0.00	
NE	0.00	0.00	0.00	0.09	0.00	0.00	
DI	14.03	6.94	18.89	15.01	10.58	15.84	
HY	7.93	16.04	0.60	0.00	3.67	2.39	
OL	61.94	65.80	72.48	68.62	74.32	52.13	
CR	0.63	0.75	0.68	0.69	0.69	0.39	
IL	0.50	0.42	0.36	0.49	0.44	0.79	
AP	0.30	0.27	0.13	0.26	0.16	0.33	

* Average of six analyses; ** Calculated with FeO=FeT
[1] XRF Pressed Pellet
[2] Internally Coupled Plasma Mass Spectrometry
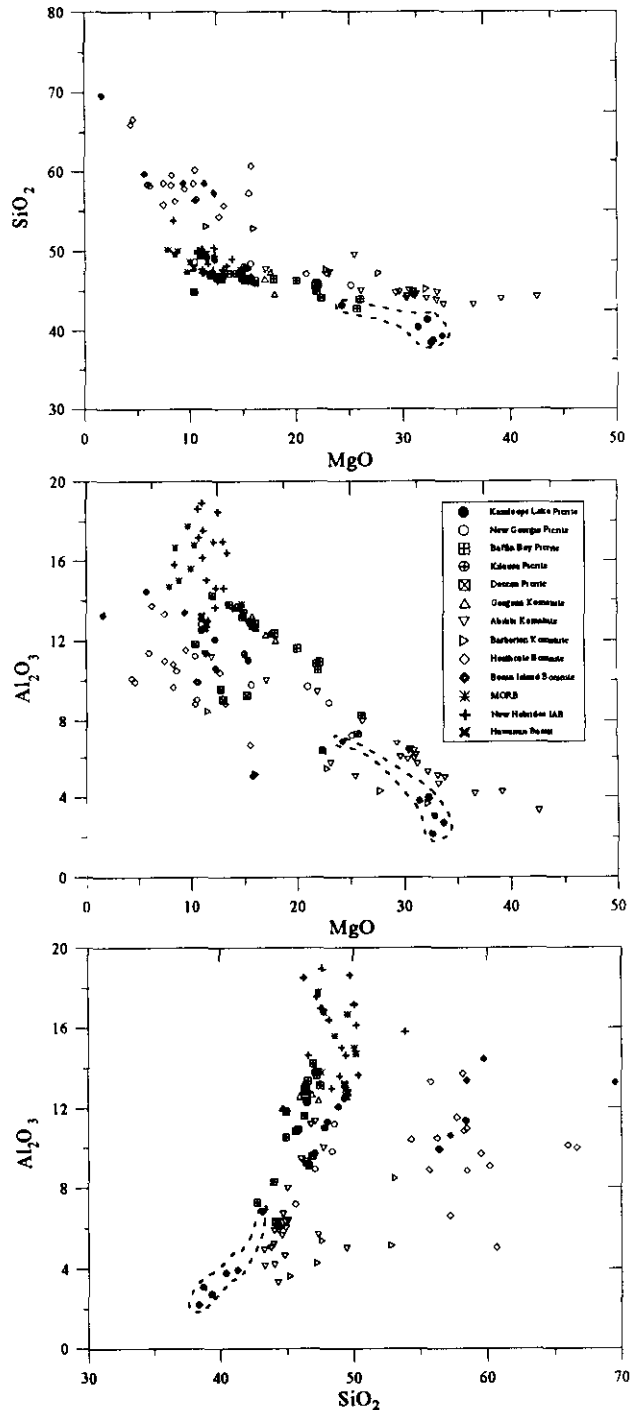CC=Carabine Creek, WC=Watching Creek, JL=Jacko Lake, IM=Iron Mask

Figure 6. Chemical compositions of Kamloops Lake picritic basalts and other suites of ultramafic rocks: (a) MgO vs SiO_2, (b) MgO vs Al_2O_3 and (c) SiO_2 vs Al_2O_3. Data sources: New Georgia (Ramsay et al., 1984), Kilauea (Nicholls and Stout, 1988), Baffin Bay (Francis, 1985), Deccan (Krishnamurthy and Cox, 1977), Abitibi (Barnes et al., 1983), Barberton (Viljoen and Viljoen, 1969), Gorgona (Echeverria, 1980), Heathcote (Crawford and Cameron, 1985), Bonin Island (Hickey and Frey, 1982), MORB (Sun and Nesbitt, 1979), New Hebrides (Dupey et al., 1982) and Hawaiian basalt (Wright, 1971).

or mineral assemblage will define a line with a predictable slope. The diagram (Figure 7) was designed by choosing an appropriate conserved element for the denominator (*e.g.*, Ti), and choosing a set of numerator elements for the x and y-axes that will model the effects of the target mineral assemblage. In Figure 7a, a cluster of open circles represents six duplicate analyses obtained from sample 92IM-108, a serpentinite from the Iron Mask batholith. An analytical error was calculated from these duplicates and applied to all other data points for the Kamloops Lake picritic basalts.
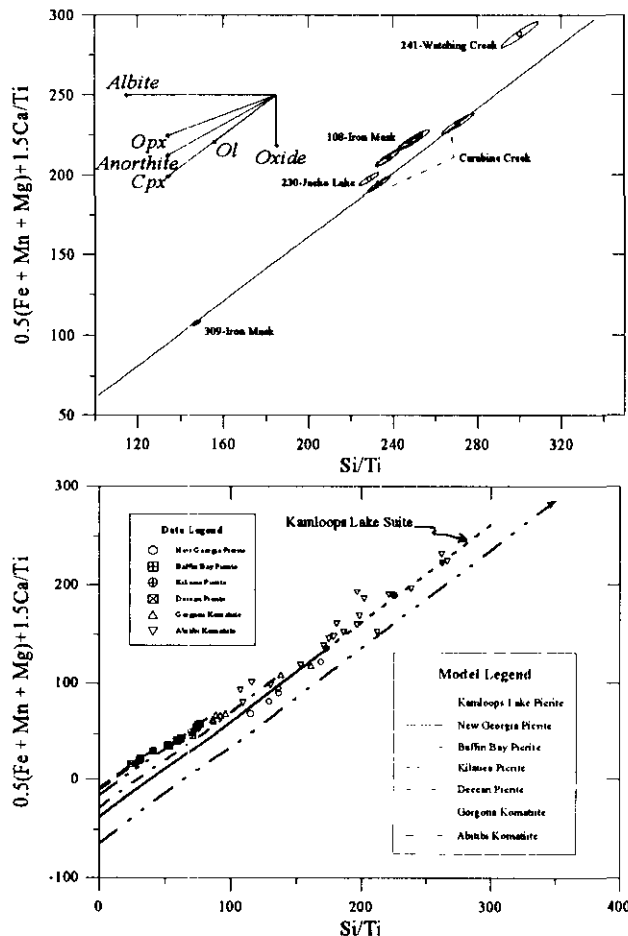
Figure 7. Chemical variation of (a) Kamloops Lake picritic basalts and (b) other mafic-ultramafic rock suites are shown as Pearce element-ratio diagrams that portray the effects of olivine and clinopyroxene. See text.

For this study, one sample from Carabine Creek (92IM-225) was chosen as the reference sample and is used as a basis for comparison for all other samples. Sample 92IM-225 is the least altered picrite obtained and displays a distinctive volcanic character.

Figure 7a tests for the cogenetic relatioi ship of the Kamloops Lake picritic basalts throug h olivine and clinopyroxene fractionation. Bot h samples from Carabine Creek plot along a s ope of one indicating that this process explains t ie chemical variation between these two sampl :s. In addition, one sample from the Iron Mask batholith is also consistent with this scenaric. Other samples from Watching Creek, Jacko Lake and the Iron Mask batholith still fail tc be explained as comagmatic by this process. Gi ven the field relationships and petrography, the nost logical explanation is that the picritic basalt : represent several magma batches (*cf,* Nicholls and Russell, 1991).

Other ultramafic suites have been plotte d for comparison on the same diagrams that were developed for the Kamloops Lake suite. Boninite suites are not shown because of the inability to conclude that titanium would be a conservec element during crystallization. The results (Figure 7b) illustrate that this method appears to consistently explain some of the crystallizati on and fractionation processes of ultramafic volcanic rocks.

The dashed line on Figure 7b represent the differentiation trend of the Kamloops Lake suite from Figure 7a. Because these rocks are enriched in MgO, they lie to the upper left of most of the suites. However, the intercept of the differentiation trend is a function of the source region. It is apparent that the intercept of the Kamloops Lake suite is very close to the intercept of the New Georgia picrites, which are an island arc suite. This implies that the source regions for these two suites of rocks may be similar.

CONCLUSIONS

The Kamloops Lake picritic basalts represent an episode of ultramafic volcanism at the later stages of Late Triassic Nicola volcanism. They lie stratigraphically above the Nicola Group arc rocks and occur as inclusions in the Early Jurassic Iron Mask batholith, w iich restricts the ultramafic lavas as a late Triass c-Early Jurassic event.

Based on relict mineralogy and textures and rock and mineral chemistry, the Iron M isk serpentinite bodies are equivalent to the picr itic basalts found at Jacko Lake, Carabine Creek and Watching Creek.

The Kamloops Lake suite shows no appreciable contamination or fractionation. The extreme forsterite content of the olivine phenocrysts is indicative of an upper mantle

source. Therefore, the suite represents primary magmas derived from the upper mantle beneath the Nicola arc during the Late Triassic. In addition, the oxidized nature of the spinels and the trace and major element chemistry further indicate that they represent ultramafic magmatism in an island arc setting.

Modeling fractionation with the Pearce element-ratio methods indicates that some picrite exposures may be cogenetic rocks related through olivine and clinopyroxene sorting. Results also indicate that the Kamloops Lake picritic magmas most likely represent more than one magma series.

ACKNOWLEDGMENTS

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NOTES