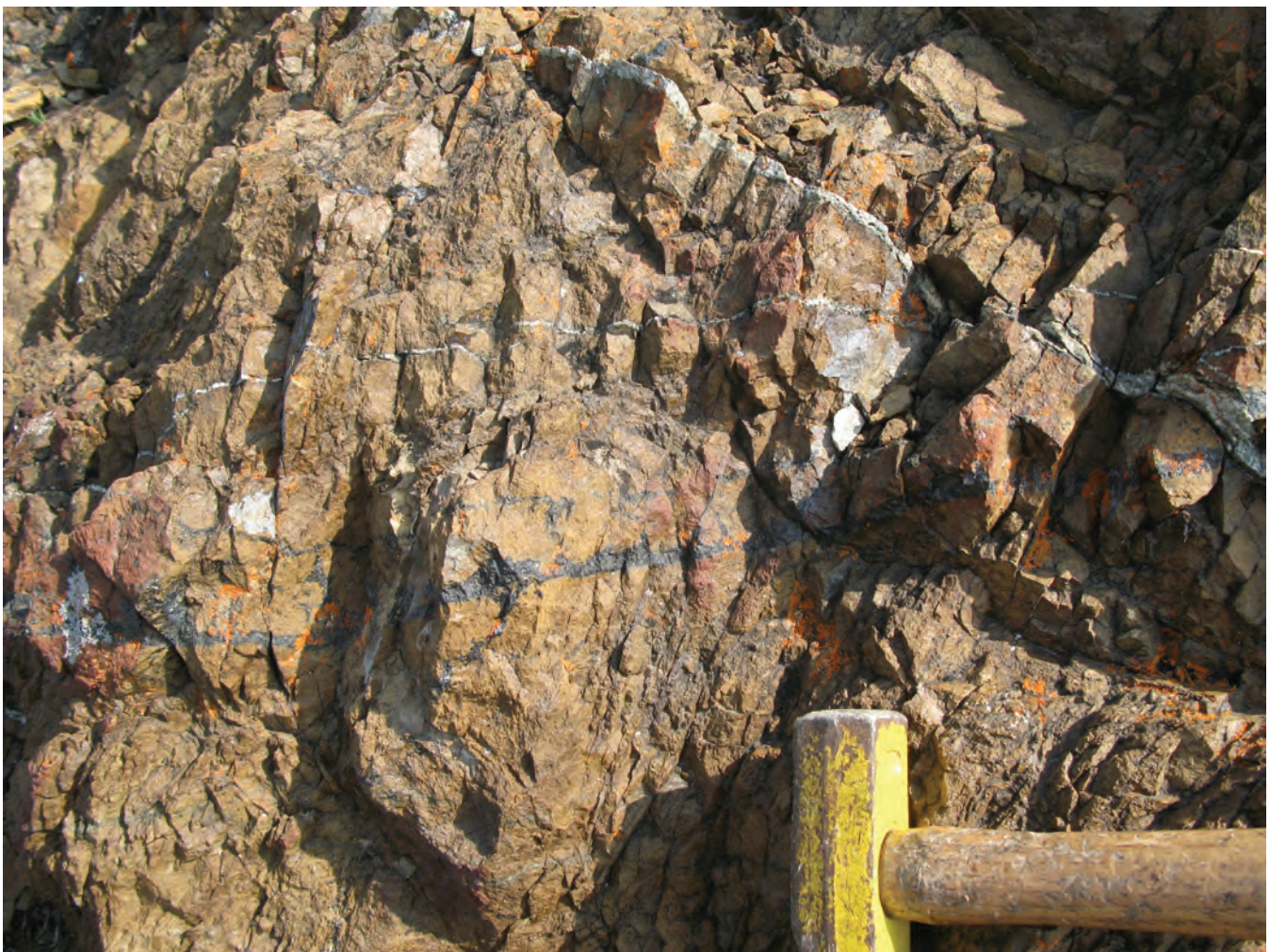**Yukon Geological Survey Open File 2012-12**

First finding of Pt-Pd-rich chromitite and platinum-group element mineralization in southwest Yukon mantle peridotite complexes

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Cover photo: Chromitite veins and gabbro dykes in sheared dunite.

PREFACE

Oceanic assemblages of the northern Canadian Cordillera (Cache Creek and Slide Mountain terranes) include volumetrically significant Alpine ultramafic complexes, about which little is known in terms of their origin(s) or mineral potential. Traditionally considered to be less attractive exploration targets than Alaskan-style mafic-ultramafic intrusive complexes, the recent discovery by First Point Minerals Corp. of the Ni-Fe alloy awaruite ($Ni_2Fe - Ni_3Fe$) in Alpine complexes in the northern Cordillera (www.firstpointminerals.com/s/Projects.asp) has spurred new interest in these ultramafic complexes. The discovery of awaruite is significant, as the occurrence of nickel and iron as an alloy rather than a silicate phase in bulk-mineable concentrations are attractive from both mining and metallurgical perspectives.

In this paper, Escayola *et al.* document another significant type of Alpine ultramafic-hosted mineralization: platinum-group-metal-enriched chromitites in mantle peridotite. They describe, and propose a genetic model for, an occurrence of chromitite veins in an ultramafic massif near Beaver Creek, Yukon, with PGE concentrations significantly higher than grades reported from PGE occurrences mined around the world. This exciting new occurrence is found in an oceanic assemblage now considered to be part of Slide Mountain terrane, the regionally extensive remnants of oceanic lithosphere that formed as the Yukon-Tanana terrane arc rifted away from the Laurentian margin during the Late Paleozoic.

The recognition of the PGE potential of ultramafic complexes of Slide Mountain affinity is further incentive to re-evaluate the importance of Alpine ultramafic complexes in the northern Cordillera, as they appear to represent a previously-undocumented metallotect. Similar complexes are exposed across large areas in the northern Cordillera, presenting exciting new exploration opportunities.

This report is a contribution to the joint Yukon Geological Survey – Geological Survey of Canada – British Columbia Geological Survey Branch "Multiple Metals Northwestern Canadian Cordillera" Project (Edges Project) under the Geo-mapping for Energy and Minerals Program of Natural Resources Canada. We sincerely appreciate the efforts of Steve Irwin, Subdivision Head of GSC Vancouver for his administrative efforts in support of this project.

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Director
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ABSTRACT

This study reports the first finding of PGE-enriched chromitite veins within mantle dunite in the Slide Mountain terrane of southwest Yukon at Eikland Mountain. Chromitite occurs as irregular centimetre-scale veins in dunite bodies within mantle harzburgite. Samples of chromitite veins contain up to 2600 ppb total PGE, with enrichment in PPGE relating to IPGE, and are characterized by a positive slope of the chondrite-normalized patterns. The PGM assemblage in the chromitite veins consists of PPGE-base metal alloys and PPGE and Os-native metal. The PPGE minerals invariably occur associated with the chromitite and Fe-Ni sulphides (pentlandite) in the olivine-rich silicate matrix.

The composition of chromian spinel in the chromitite veins is homogeneous although it is highly variable throughout the complex. Vein chromian spinel has low Cr# (~0.45), moderate Mg# (0.58-0.64), low Fe^{3+}# (0.03-0.05) and relatively high TiO2 contents (0.410.62wt%). The chromian spinels contain inclusions of Na-rich amphibole, apatite, rutile and phlogopite. In addition, they host PtFeCu, PtFe alloys, native Pt, abundant Hg-Pd (potarite), isoferroplatinum, tulameenite, sperrylite and Cu sulphides.

This mineralization is interpreted as small volumes of alkaline melts extracted at moderate to high oxygen fugacity from deep levels of an upwelling mantle that were trapped in cracks and reacted with the host peridotite crystallizing in the form of discordant chromitite veins. This process took place during, or a short time after, the formation of mantle shear zones at early stages of mantle lithosphere extension, which we infer to have occurred during the initiation of intraoceanic subduction at Slide Mountain Ocean on the passive margin of the Yukon-Tanana terrane.

INTRODUCTION

Ultramafic complexes form a volumetrically significant part of two mafic-ultramafic assemblages in western Yukon. Little studied until recently, these assemblages have not been fully characterized in terms of their lithological composition, age, geochemical attributes, terrane affiliation, mineralization, and consequently their roles in Cordilleran evolution have been largely undefined. Rocks of the Harzburgite Peak – Eikland Mountain assemblage extend southwestwardly across Stevenson Ridge map area (Fig. 2). The assemblage has been tentatively assigned to the Slide Mountain terrane (Canil and Johnston, 2003), a Sea-of-Japan-like marginal oceanic terrane which was formed by seafloor spreading behind an ensialic arc terrane (Yukon-Tanana terrane) as the latter rifted away from the Laurentian margin during late Paleozoic subduction rollback (Nelson, 1993; Creaser *et al.*, 1999; Colpron *et al.*, 2006). This correlation has been recently affirmed on the basis of unpublished age and geochemical data (*e.g.*, Murphy, 2011; Murphy *et al.*, 2011; Escayola *et al.*, in prep.) and its newly recognized position between Yukon-Tanana terrane and rocks recently correlated with the Laurentian margin, the structural position generally occupied by Slide Mountain terrane elsewhere in the Cordillera (Figs. 1, 2; Dusel-Bacon *et al.*, 2006; Murphy, 2011; Murphy *et al.*, 2011).
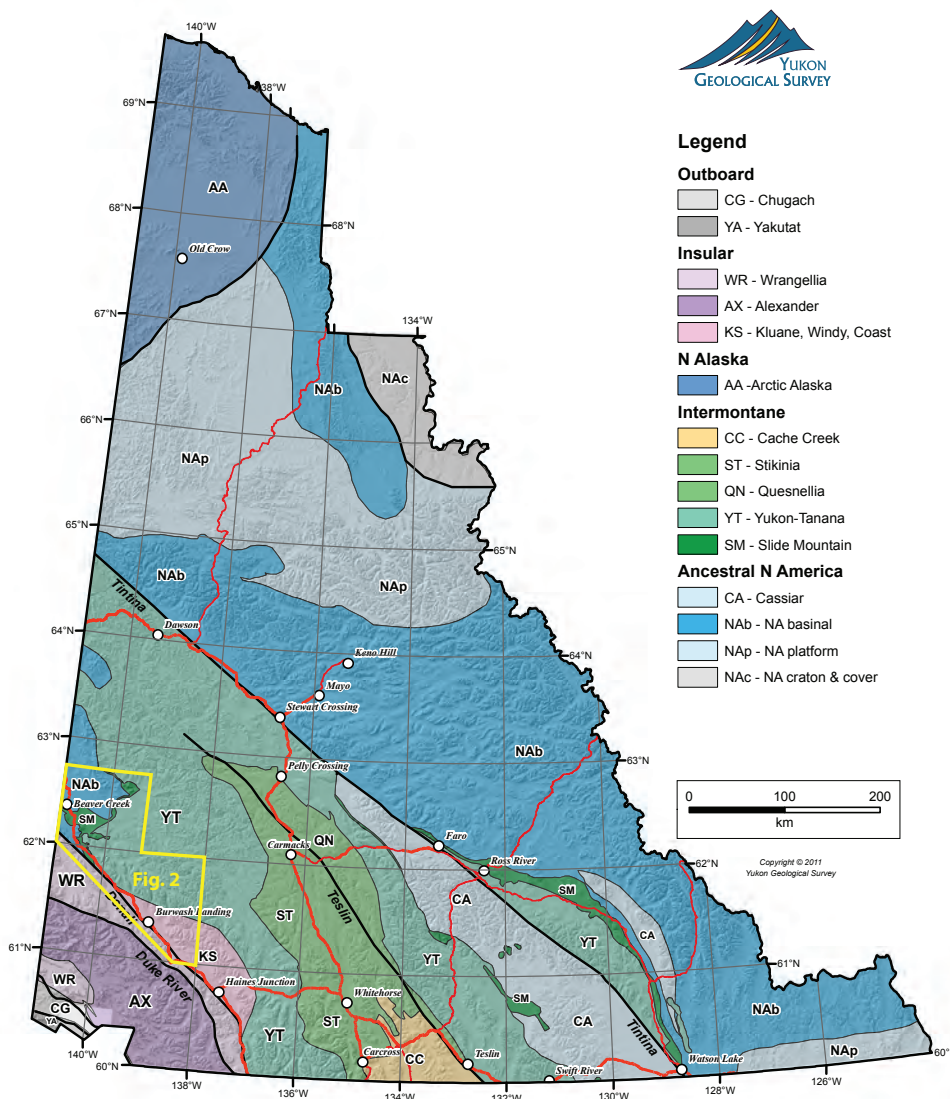

Figure 1. Terrane map of Yukon (modified from Colpron and Nelson, 2011). Location of western Yukon study area is indicated by yellow box.

Rocks of the Doghead assemblage are found in Kluane Lake map area south of the occurrences of the Harzburgite Peak – Eikland Mountain assemblage (Fig. 2). The Doghead assemblage comprises klippe of peridotite, gabbro, and plagiogranite overlying the western margin of Yukon-Tanana terrane from Doghead Point on Kluane Lake northwestwardly to the northwestern side of the Donjek River (Fig. 2). Originally included in the Harzburgite Peak – Eikland Mountain assemblage (Murphy *et al.*, 2009), unpublished age and geochemical data for the Doghead assemblage (*e.g.*, Murphy, 2011; Murphy *et al.*, 2011) suggest a correlation with the Chulitna terrane of central Alaska, a Late Triassic intraoceanic arc terrane (*e.g.*, Murphy *et al.*, 2011).
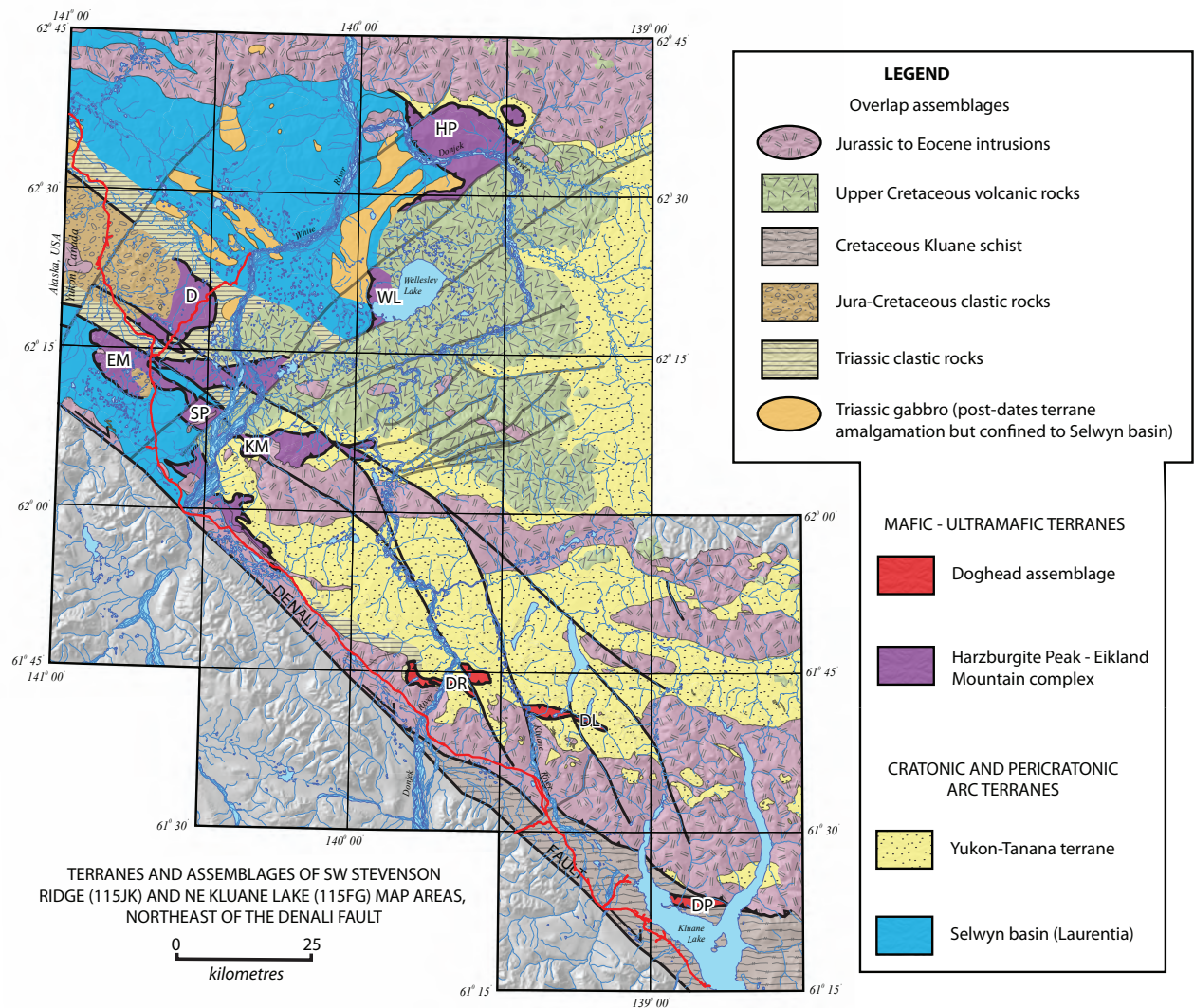
Figure 2. *Geological elements of western Yukon. Locations referred to in text: KM-Koidern Mountain; EM-Eikland Mountain; HP-Harzburgite Peak; SP-Sanpete Hill; WL-Wellesley Lake; D-Deadman Hill; DR-Donjek River; DL-Dogpack Lake; DP-Doghead Point.*

In this paper we present the results of a field, geochemical, and petrological study of chromitite veins in mantle ultramafic rocks of the Harzburgite Peak – Eikland Mountain assemblage. Chromian spinel is an important mineral constituent of ultramafic rocks; the nature of its occurrence and its geochemical and petrological character provide important clues to the origin and evolution of the ultramafic rocks, and hence to their significance in Cordilleran evolution. In our study the nature of occurrences of chromitites in the field is described along with the mineralogical and geochemical character of the occurrences. The data are then integrated into a model for the formation of the chromitites and PGE mineralization.

LOCAL GEOLOGY AND PETROGRAPHY

The Harzburgite Peak – Eikland Mountain assemblage comprises peridotite, mafic plutonic and volcanic rocks, and rare chert and argillite which are exposed discontinuously in isolated outcrops across the Stevenson Ridge map area (Fig. 2). Although thought to be structurally imbricated (Canil and Johnston, 2003), the rock units are coherent and melange-free. Murphy *et al.* (2009) interpreted the assemblage as a supra-subduction zone (SSZ) ophiolitic sequence although a complete, structurally intact ophiolite section from mantle rocks to sea-floor sedimentary rocks has not been documented. In the northeast, the

Harzburgite Peak massif is composed primarily of mantle peridotite in its southern part, and peridotite, massive medium-grained pyroxene gabbro, diabase, rare coarse-grained hornblende gabbro, and rare basaltic volcanic rocks in the north; Canil and Johnston (2003) infer a thrust fault between these two areas. Chert, argillite, diabase, and relatively featureless basalt occur west of Wellesley Lake (Fig. 3a; Wellesley Lake formation of Murphy *et al.*, 2008), on Deadman Hill and on Koidern Mountain (Fig. 2). Variably porphyritic diabase and microgabbro, generally lacking sheeted dyke structure, make up the majority of Sanpete Hill (Figs. 2 and 3b). In addition to chert and argillite, Koidern Mountain also comprises diabase, minor peridotite, and a voluminous body of hornblende gabbro which intrudes into the supracrustal rocks (Fig. 3c). The hornblende gabbro is *ca.* 274 Ma and is geochemically and isotopically primitive with a geochemical composition compatible with a nascent arc setting (*e.g.*, Murphy *et al.*, 2011; Escayola *et al.*, in prep.).

The Harzburgite Peak – Eikland Mountain assemblage differs in many ways from the "ideal ophiolitic sequence" defined at a 1972 Penrose conference on ophiolites (Anonymous, 1972). The assemblage largely consists of peridotite having a low degree of serpentinization, and a poorly developed crustal sequence characterized by little gabbro; some diabase, lacking sheeted structure; and rare basaltic volcanic and sedimentary rocks. Peridotite is locally intruded by gabbro veins, and small volumes of hornblende gabbro intrude the discontinuous supracrustal basaltic and sedimentary cover. The assemblage lacks a simple-layered structure and to a certain extent resembles ultramafic complexes formed along a slow-spreading ridge (Dick, 1989; Cannat, *et al.*, 1995; Dick *et al.*, 2006; Escayola *et al.*, in prep.) or orogenic mantle massifs (*cf.* Bodinier and Godard, 2003)[1].

Peridotite

Peridotite is the dominant rock type of the Harzburgite Peak and Eikland Mountain massifs (Fig. 2). Harzburgite Peak is a 70 km^2 ultramafic massif made up of a variety of peridotite lithologies. Harzburgite is the most common peridotite type, ranging in composition from orthopyroxene (Opx)-rich (>30 vol% Opx) to Opx-poor (<10%); dunite occurs locally. Clinopyroxene is generally 1-2 vol% of the peridotites, although local concentrations (mainly south of Harzburgite Peak) may be up to 5 vol%. A crude orthopyroxene layering is locally observed, but in general the rocks are coarsely granular and massive (Fig. 3d). Layering is centimetre-scale and defined by a variable olivine/orthopyroxene ratio. Olivine is recessive whereas orthopyroxene (1-2 cm-sized crystals) and spinel-clinopyroxene symplectites (up to 3 mm in diameter) are resistant, resulting in a knobby weathered surface. Melt-related mantle structures such as replacive dunite lenses (Kelemen and Dick, 1995) and orthopyroxenite veins and dykes are widely present. Replacive dunite lenses are metre scale and bonded to surrounding harzburgite by layers of spinel clinopyroxene (cpx) harzburgite.

Eikland Mountain is a 40 km^2 ultramafic massif consisting largely of dunite and harzburgite (Fig. 2). Harzburgite at Eikland Mountain locally has features indicative of mantle deformation and is more serpentinized (20%) than at the Harzburgite Peak massif. These features suggest a location at the upper structural levels of the peridotite section, nearest to the Moho Transition Zone. Dunite composes approximately 60% of the ultramafic complex. Dunite is foliated, and field observations suggest that it formed as a result of porous reactive flow in ductile shear zones and around propagating cracks. Reactive flow between hydrous melts and residual peridotite at temperatures less than 1100°C is thought to be common near the brittle-ductile transition in shallow mantle lithosphere (Kelemen and Dick, 1995).

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1   Orogenic massifs are dispersed ultramafic bodies in suture zones and mountain belts, a few metres to kilometres in size, and differing from ophiolitic peridotites in being unrelated to oceanic rock associations, and in some massifs containing shallow intrusive rocks interpreted as embryonic ocean crust.

Figure 3. *a) Highly foliated ribbon chert from the Wellesley Lake formation, west of Wellesley Lake, b) rare sheeted diabase dykes found at Sanpete Hill, c) hornblende gabbro from Koidern Mountain, and d) harzburgite with orthopyroxenite veins, Harzburgite Peak.*

Gabbro (clinopyroxene-plagioclase) and pyroxenite dykes, ~10 cm wide, crosscut dunite at Eikland Mountain (Fig. 4a). These dykes are undeformed and highly discordant to the high-temperature foliations in the dunite and residual peridotite. These dykes are indicative of crystallization from an evolved low-temperature liquid. Although their age is unknown, their geochemical composition resembles that of the *ca.* 274 Ma gabbro located on Koidern Mountain (Escayola *et al.*, in prep.).

CHROMIAN SPINEL AND CHROMITITE VEINS

Chromian spinel is a constituent of peridotites at both Harzburgite Peak and Eikland Mountain. Accessory chromian spinel is common in dunite at Eikland Mountain. Chromian spinel increases in

quantity and size in proximity to irregular chromitite veins and stockworks found on Eikland Mountain (Fig. 4a). The stockworks appear to be associated with late shear zones within the dunite tectonite. The contact between chromitite and its host rock (dunite) is either sharp or gradual, defined by a zone of disseminated chromian spinel sometimes tens of metres wide. The lateral extent of the chromitite bodies varies between one and five metres and the thickness between 1 and 15 cm. The most common texture of the chromitite is massive, containing euhedral to subhedral chrome spinel grains ranging from 2 to 5 mm in diameter. In thin section, chromitites show massive magmatic textures represented by equilibrium triple junctions between large chromian spinel grains, possibly derived from annealing and sintering processes at high temperature (Fig. 4b). No ferrichromite alteration or pull-apart fractures are observed. Chromian spinel grains contain abundant primary solid, single or composite, 0.1 to 1 micron-sized inclusions of calcite, rutile, Na amphibole, albite, and apatite (Fig. 4c). Interstitial silicates include mainly olivine immersed in a thin matrix of serpentine. Accessory pentlandite is locally incipiently altered to awaruite-type Ni-Fe alloy; magnetite and minor Ni-sulphides (pentlandite) also occur in the matrix (Fig. 4d).

Disseminated chromian spinel also occurs at Harzburgite Peak; to date chromitite veins have not been observed there.
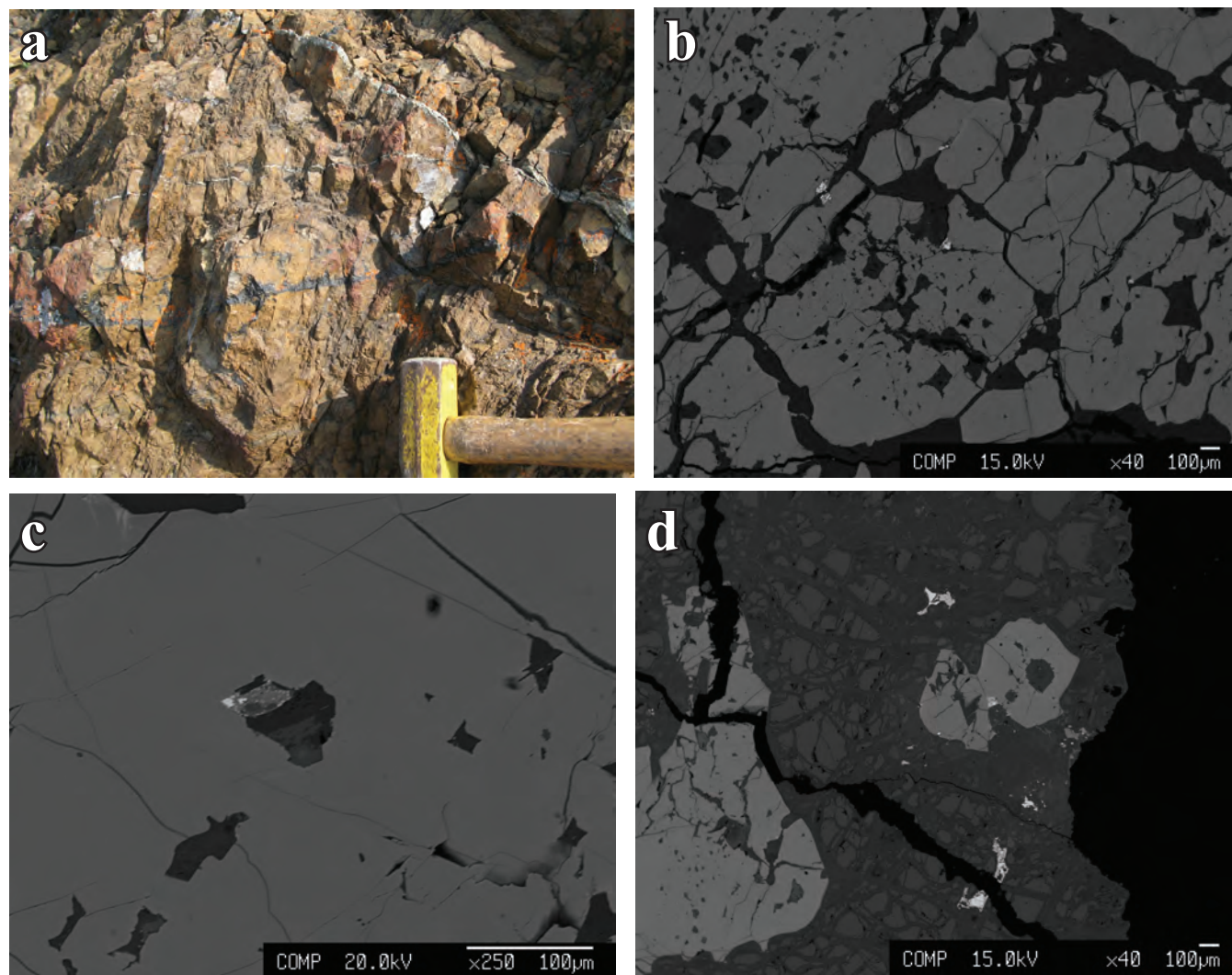

Figure 4. a) Thin gabbro dykes (white) and chromitite veins in sheared dunite, b) massive chromitite exhibiting magmatic textures, c) phlogopite and calcite inclusions in chromitite, and d) pentlandite in the olivine matrix in dunite hosting chromitite veins.

ANALYTICAL TECHNIQUES

Electron microprobe analyses of chromian spinel and olivine were carried out on polished sections from massive chromitite and high-grade chromian spinel disseminations in dunite. Analyses were conducted using a four-channel CAMECA SX50 electron microprobe at the Serveis Cientificotècnics of the Universitat de Barcelona. Mineral compositions were obtained by analysing several grains in each section. The analytical conditions were 20 kV accelerating voltage, 20 nA beam current, 2 μm beam diameter, and counting time of 10 seconds per element. Calibrations were performed using natural and synthetic reference materials: chromite (Cr, Al, Fe), periclase (Mg), rhodonite (Mn), rutile (Ti), NiO (Ni) and metallic V. The proportion of trivalent iron in chromian spinel was calculated assuming stoichiometry.

Samples of massive and disseminated chromitite and the enclosing dunite were analysed for platinum-group elements (PGE) at the Genalysis Laboratory Services Pty. Ltd. at Maddington, Western Australia. The samples were analysed by ICP-MS after concentration from nickel sulphide fire-assay collection. Detection limits were 1 ppb for Rh, 2 ppb for Os, Ir, Ru, Pt, Pd, and 5 ppb for Au.

The PGM were initially investigated *in situ* in polished sections and subsequently on heavy concentrates obtained using a hydro-separation technique at the Universitat de Barcelona. The PGM were then analysed by reflected-light and scanning-electron microscopy at the Eugen F. Stumpfl Laboratory (Leoben University), using a Superprobe Jeol JXA 8200. The same instrument, operated in the WDS mode, at 20 kV accelerating voltage, and 10 nA beam current was used for quantitative analysis. The beam diameter was approximately 1 μm. The PGM were analysed using pure metals as the reference material for PGE, synthetic NiS and Pd3HgTe, natural pyrite, chalcopyrite and niccolite for Fe, Ni, Cu, S, Hg, and As. The X-ray lines used were: Kα for S, Fe, Cu, and Ni; Lα for Ir, Ru, Rh, Pt, and As; and Mα for Os and Hg. The following diffracting crystals were selected: PETJ for S and Hg; PETH for Ru, Os, and Rh; LIF for Cu; LIFH for Ni, Ir, and Pt; and TAP for As. The counting time for peak and both backgrounds (left and right) were 20 and 10 seconds respectively. Automatic corrections were performed for interferences involving Ru-Rh, Ir-Cu, and Rh-Pd. The same analytical lines and diffracting crystals were used to obtain the elemental distribution maps. The grains found *in situ* were only qualitatively analysed using EDS, due to their small size. Heavy mineral concentration by means of hydro-separation (HS11) (Rudashevsky and Rudashevsky, 2001, 2006, 2007 and refer to http://cnt-mc.com/) was applied at the University of Barcelona to find PGM of sufficient grain size for quantitative analysis. Within a 652 g dunite sample containing zones of massive chromitite, this technique led to the discovery of 70 PGM grains; the largest PGM grain measured 40μm in diameter.

Chromian spinel composition

Primary chromian spinel from Eikland Mountain chromitite (Table 1) is compositionally homogeneous in terms of major oxides, with narrow variations in Cr_2O_3 (36.25-39.26 wt%), Al_2O_3 (27.09-31.56 wt%), MgO (13.75-14.79 wt%), and FeO (14.84-15.95 wt%). TiO_2 contents are relatively high (0.41-0.62 wt%) compared to those in typical ophiolitic chromitites (< 0.3 wt%, Dickey, 1975). Calculated Fe_2O_3 ranges 2.2-4.33 wt%. The amounts of MnO, V_2O_3 and ZnO are lower than 0.31 wt%, 0.22 wt% and 0.21 wt%, respectively.

Eikland Mountain chromitites show little variation on a Cr# [= Cr/(Cr+Al)] vs Mg# [= Mg/(Mg+Fe^{2+})] diagram (Fig. 5). They generally have a moderate Mg# and a relatively low Cr# range (0.43-0.52). The chromian spinel compositions plot in the field of abyssal peridotites, however TiO_2 content is not consistent with abyssal tectonic settings and resembles chromian spinel in equilibrium with alkaline basalts representing low degrees of melting (Ocean Island Basalts (OIBs); Crockett, 2002).

Table 1. Microprobe analyses. Chromite chemical composition.

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	0.07	0.00	0.05	0.04	0.04	0.05	0.00	0.06	0.02	0.02	0.04	0.02
TiO_2	0.51	0.56	0.49	0.41	0.37	0.53	0.55	0.54	0.62	0.62	0.59	0.58
Al_2O_3	30.46	31.56	31.61	30.47	31.41	28.39	28.49	27.56	27.09	29.61	29.58	28.91
Cr_2O_3	37.20	35.88	36.25	37.16	36.45	37.81	38.43	38.98	39.26	35.18	35.46	35.87
Fe_2O_3	2.61	2.86	2.20	2.86	2.29	3.86	4.13	4.14	4.33	4.27	4.22	4.88
FeO	14.88	14.84	15.19	14.92	14.93	15.83	15.65	15.95	15.59	16.72	16.90	16.06
V_2O_3	0.09	0.21	0.19	0.14	0.14	0.00	0.15	0.12	0.18	0.25	0.10	0.11
MnO	0.24	0.17	0.19	0.18	0.25	0.19	0.20	0.20	0.31	0.30	0.28	0.32
MgO	14.54	14.79	14.49	14.46	14.54	13.75	14.05	13.77	13.81	13.12	13.05	13.50
ZnO	0.11	0.12	0.12	0.21	0.08	0.00	0.13	0.06	0.21	0.18	0.14	0.09
NiO	0.20	0.12	0.18	0.17	0.07	0.17	0.17	0.14	0.15	0.12	0.14	0.15
Total	100.91	101.11	100.97	101.02	100.57	100.57	101.95	101.52	101.58	100.40	100.47	100.48
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ti	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Al	1.05	1.08	1.09	1.05	1.08	1.00	0.99	0.96	0.95	1.04	1.04	1.02
Cr	0.86	0.83	0.84	0.86	0.84	0.89	0.89	0.91	0.92	0.83	0.84	0.85
Fe^{3+}	0.06	0.06	0.05	0.06	0.05	0.09	0.09	0.09	0.10	0.10	0.10	0.11
Fe^{2+}	0.37	0.36	0.37	0.37	0.37	0.39	0.39	0.40	0.39	0.42	0.42	0.40
V	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Mn	0.01	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.64	0.64	0.63	0.63	0.63	0.61	0.62	0.61	0.61	0.58	0.58	0.60
Zn	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Ni	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr#	0.45	0.43	0.43	0.45	0.44	0.47	0.48	0.49	0.49	0.44	0.45	0.45
Mg#	0.64	0.64	0.63	0.63	0.63	0.61	0.62	0.61	0.61	0.58	0.58	0.60

Cations calculated on the basis of 32 oxygens

PGE GEOCHEMISTRY

Massive chromitites from Eikland Mountain contain up to 2600 ppb of total PGE (Table 2). Dunite containing concentrations of disseminated chromian spinel ranges up to 153 ppb total PGE and harzburgite contains 40 ppb of total PGE.

Chondrite-normalized PGE patterns of both massive and disseminated chromian spinel in dunite (Fig. 6a,b) are characterized by a strong partition between a positive slope for Rh+Pd+Pt (PPGE) and a flat slope for Os+Ir+Ru (IPGE). The harzburgite has the same relative distribution of PGEs as the chromitite-dunite assemblage (Fig. 6b). This PGE distribution is unusual compared with other types of PGE-bearing ultramafic complexes around the world (Fig. 6). Positive-sloping Rh+Pd+Pt (PPGE) patterns are well known in layered ultramafic complexes (Fig. 6a, Upper Group, Bushveld; selected stratiform), with increasing enrichment of all six PGEs from Os to Pd (see Naldrett *et al.*, 2009). Naldrett *et al.* (2009) also point out that the relative proportion of (Pt+Pd)/(Rh+Ru+Ir+Os) is much
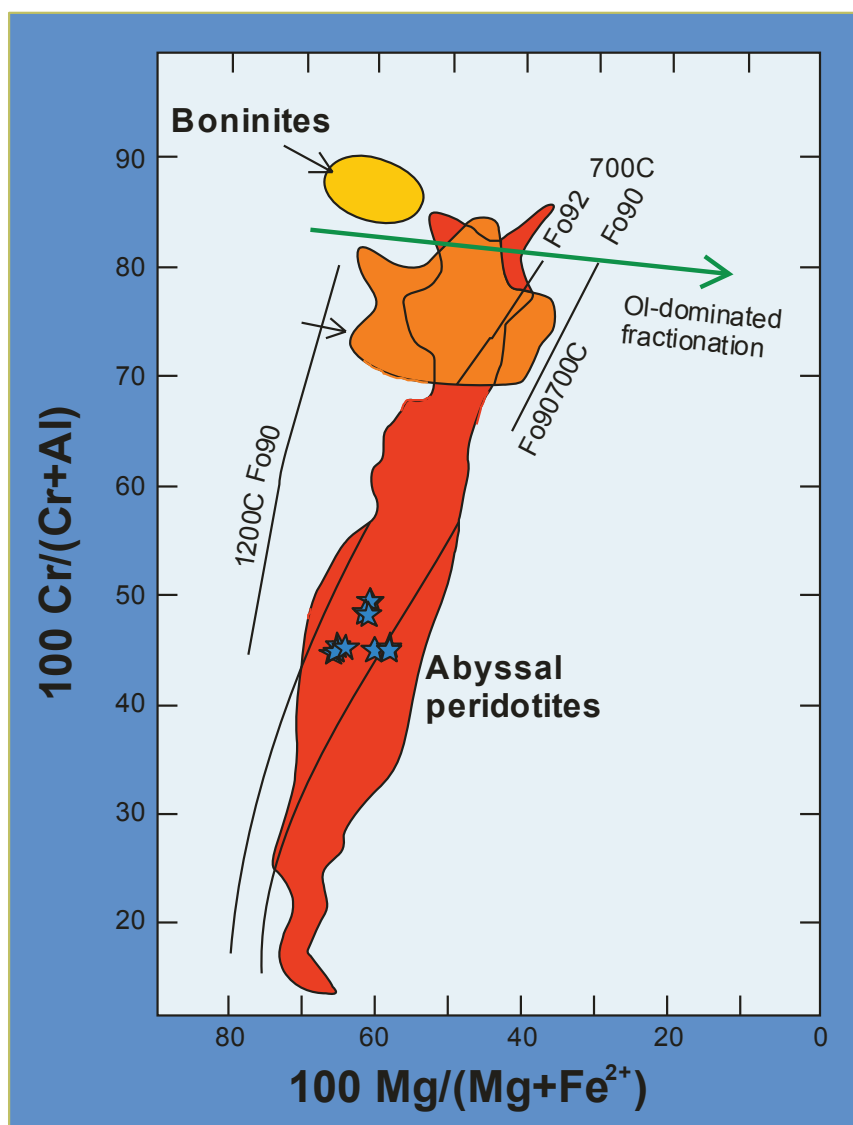
Figure 5. *#Cr vs #Mg diagram for Eikland Mountain massive chromitite veins.*

lower in many of the chromitites that occur in ophiolite complexes than those in layered intrusions. Most podiform chromitites in ophiolites are characterized by negative slopes for PGE in chondrite-normalized diagrams, with chondrite-normalized values for Ru, Ir, and Os exceeding those for Pt and Pd, typically by 1 to 2 orders of magnitude (Fig. 6a, selected ophiolite). However, there are some exceptions to the above generalization. Prichard *et al.* (1996) drew attention to the high Pt and Pd concentrations in the Cliff chromitite in the Unst (Shetland Islands) ophiolite (Fig. 6a, Shetland ophiolite). Prichard *et al.* (2008) reported bodies of podiform chromitites, some having positive and some having negative slopes in the Al'Ays ophiolite in Saudi Arabia. These authors also attributed the unusual Pt and Pd-rich bodies to crystallization from less magnesian melts, for which the degree of melting necessary to dissolve all sulphide in the melting zone was just exceeded.

Table 2. Platinum group elements and gold in ultramafic samples and chromitites from Eikland Mountain.

| Elements	Au	Au-Rp1	Ir	Os	Pd	Pd-Rp1	Pt	Pt-Rp1	Rh	Ru
Units	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
Detection	5	1	2	2	2	1	2	1	1	2
Method	NIS/MS	FA25/MS	NIS/MS	NIS/MS	NIS/MS	FA25/MS	NIS/MS	FA25/MS	NIS/MS	NIS/MS
Sample Numbers										
09-VL-E-A5-01	18		4	4	3		4		2	6
09-VL-E-A6-04	11		4	4	16		3		2	6
09-VL-E-A10-01	6		3	4	7		5		2	5
09-VL-E-A11-01	6		3	3	9		10		3	5
09-VL-E-A12-01	29		X	X	47		37		1	X
09-VL-E-A13-01	7		7	9	13		15		5	11
09-VL-E-A16-02	8		8	6	65		57		7	8
09-VL-E-A16-03	21		5	3	47		32		4	5
09-VL-E-A17-02	51	49	139	158	689	885	903	1056	125	192
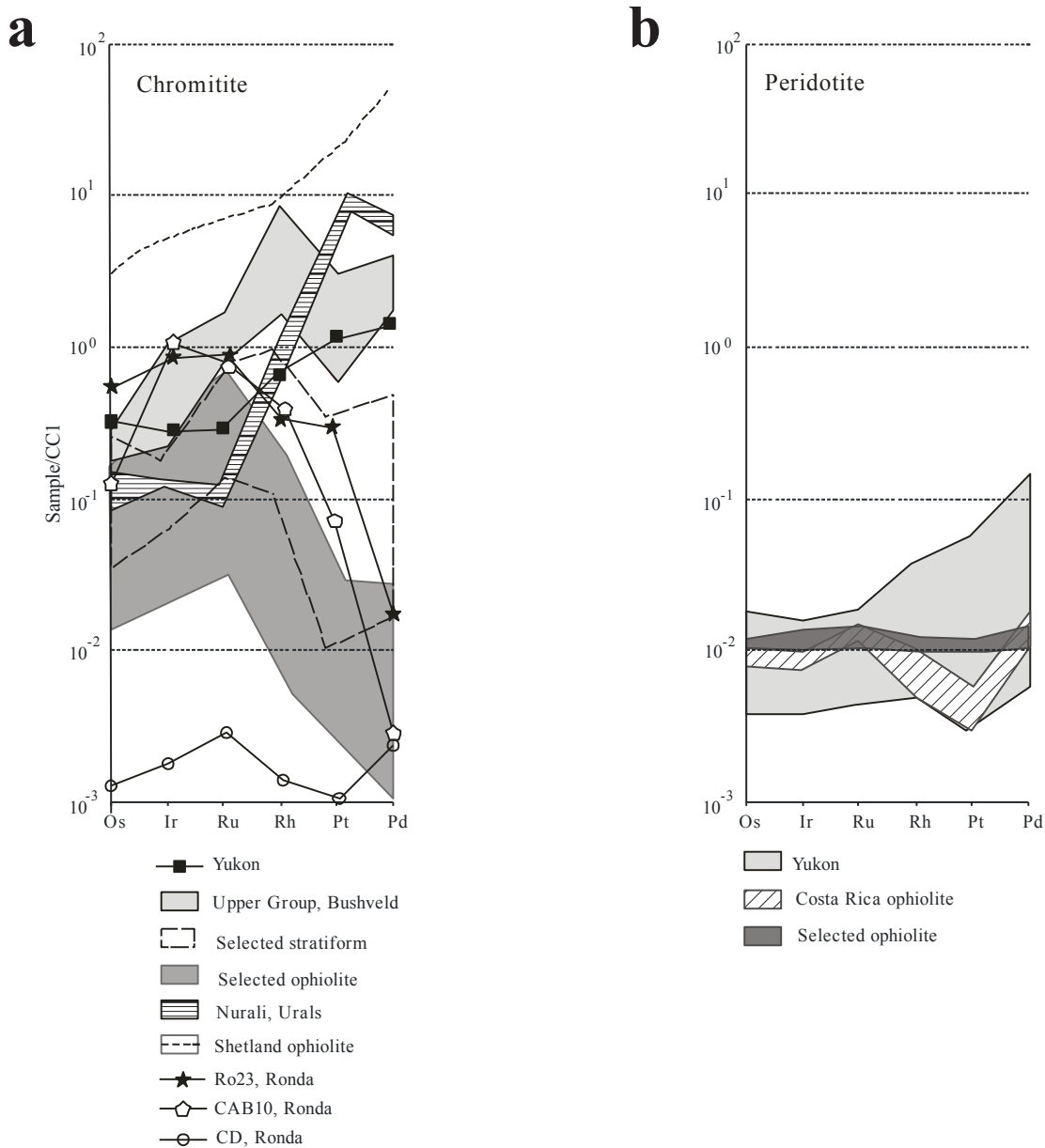
Figure 6. *Platinum Group Element patterns for Eikland Mountain: a) massive chromitites, b) dunite and harzburgite. Similar data from other types of ultramafic complexes are included for comparison.*

PGE patterns of orogenic mantle massifs, such as the Ivrea Zone (Italy) and the Betic – Rifean Cordillera (Ronda in Spain and Beni Boussera in Morocco), in general are reminiscent of those of chromitites from ophiolite complexes, having positive slopes for Os-Ir and negative slopes (Ru-Rh-Pt-Pd) (Torres Ruiz *et al.*, 1996), but with slight variations from one locality to the other (Fig. 6a, Ro23, Ronda; CAB10, Ronda; CD, Ronda). However, in orogenic mantle massifs the average PGE content is higher and the slope in Ru-Rh-Pt-Pd less steep (Fig. 6a). Platinum-group-element distribution of these types of complexes were discussed in detail by Garuti *et al.* (1997a) and they show that mantle-normalized patterns of peridotites grade from nearly flat or slightly PPGE-enriched in lherzolites to clearly negative and PGE-depleted in residual harzburgites and dunites. Although PGE abundance in some dyke rocks representing polybaric derivates of basaltic melts (pyroxenites and gabbros), most coming from the underlying asthenosphere, show higher contents in PGE (up to 250 ppb) and positive

mantle-normalized patterns. These higher PGE concentrations are observed in strongly deformed, possibly older Cr websterites. The high total amount of PGE in the PGE-rich dykes are mainly due to high Pt and Pd (Garuti *et al.*, 1997a) and this enrichment systematically occurs in mantle peridotites collected adjacent to PGE-rich dykes.

Uralian-Alaskan-type complexes, though with local variations (see Garuti *et al.*, 1997b, and Garuti *et al.*, 2003), display M-like patterns with marked peaks of Pt and Ir (Fig. 6a, Nurali, Urals). The mineralogy found in Type III chromitites by Garuti *et al.* (2003) is very similar to Eikland Mountain chromitites shown in the present study (see below), composed of a PGM assemblage that consists of irarsite, tulameenite, Pt-Pd-Cu, Pt-Cu alloys along with Pd-rich copper, and Rh-Sb-S (not found in Yukon). Chromitites containing these assemblages are extremely Fe-rich with #Fe^{2+} (0.66) and #Fe^{3+} (0.59), considerably higher than Eikland Mountain chromitites (#Fe^{2+} (0.36-0.40) #Fe^{3+} (0.3-0.5)).

The experimental work carried out by Mungall *et al.* (2006) includes PGE concentrations with similar PGE patterns to this study in Eikland Mountain PPGE-rich chromitites (Fig. 7). In their research the authors document very high, unfractionated, chalcophile element concentrations in low-degree partial melts from the mantle that cannot be reconciled with the widespread residual sulphide assumption that when partial melts are extracted from the upper mantle, sulphide liquid in the restite sequesters chalcophile elements until the extent of partial melting exceeds 25% and all sulphide has been dissolved in silicate melt. They show that the observed high, unfractionated platinum-group-element concentrations in low-degree partial melts can be attained if the melting takes place at moderate-to-high oxygen fugacity, which will reduce the amount of sulphide due to the formation of sulfate and will also destabilize residual monosulphide solid solution by driving melts into the spinel-liquid divariant field. The consequence of this process will be the crystallization of chromian spinel associated with Pt and Pd alloys and lack of sulphide mineralization.
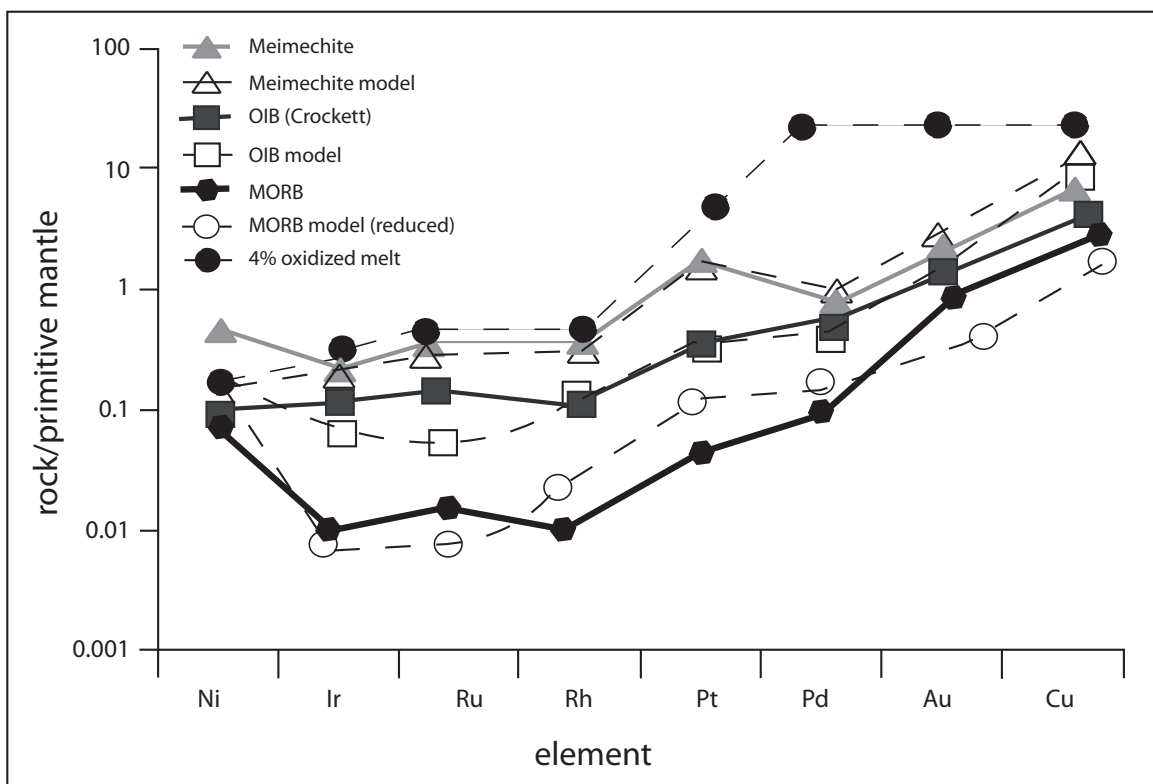

Figure 7. *Experimental PGE pattern for low degrees of melting basalts after Mungall et al. (2006).*

MINERALOGY AND COMPOSITION OF THE PGM

The mineralogy and composition of the PGM in the Eikland Mountain chromitites (Fig. 8a,b) are consistent with bulk rock geochemical data. PGMs include PPGE-bearing phases that are particularly abundant, accounting for the positive slope of the chondrite-normalized PGE patterns. These phases are: Hg-Pd alloys (potarite), Pt-Pd alloys, Fe-Ni-Pt alloys, base metal (BM)-bearing (Pt-Pd)-alloys, (Pt-Pd)-bearing BM alloys, and Fe-Cu-Pt compounds. All PGMs observed in thin section occur within the silicate matrix or chromitite silicate inclusions, or are associated with interstitial pentlandite and Fe oxides. Scarce PGMs have been found as 1 to 20 µm-sized inclusions in chromite crystals.
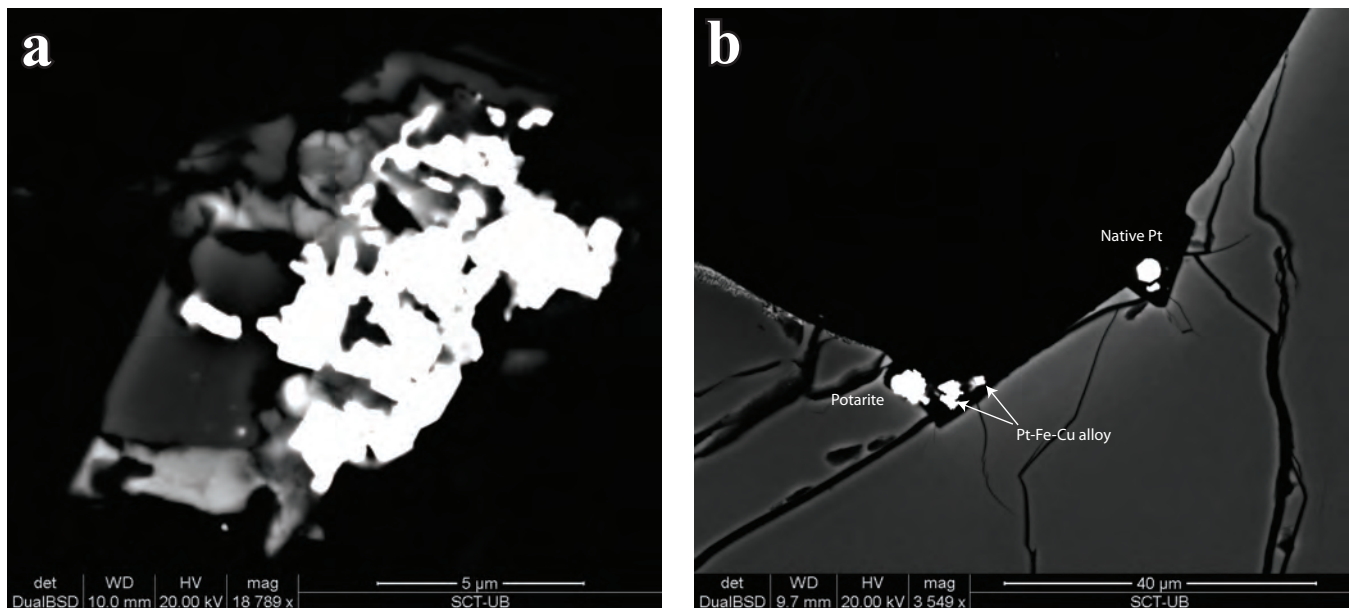

Figure 8. *Back-scattered-electron (BSE) microphotographs: a) Pt-Fe-Cu alloy in pentlandite in chromitite, b) from left to right: Hg-Pt-Pd (potarite), Pt-Fe-Cu alloy, native Pt.*

In heavy mineral concentrates, two groups of PGM occur: small (<5 µm) potarite grains associated with pentlandite as well as Fe oxides; and free PGM grains (up to 40 µm) of potarite, isoferroplatinum, tulameenite, and sperrylite (Fig. 9a,b).
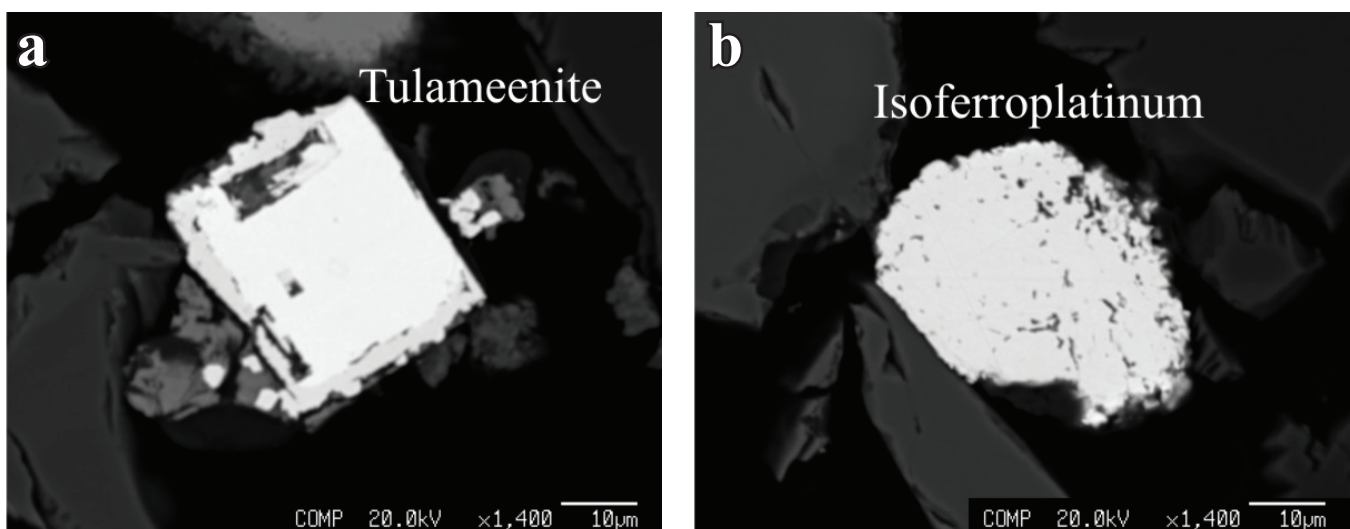

Figure 9. *PGM grains (up to 40 um): a) tulameenite and b) isoferroplatinum.*

Quantitative analyses of PGM within the Pt-Fe-Cu-Ni system have been plotted as atomic % in the ternary diagram of Fig. 10.
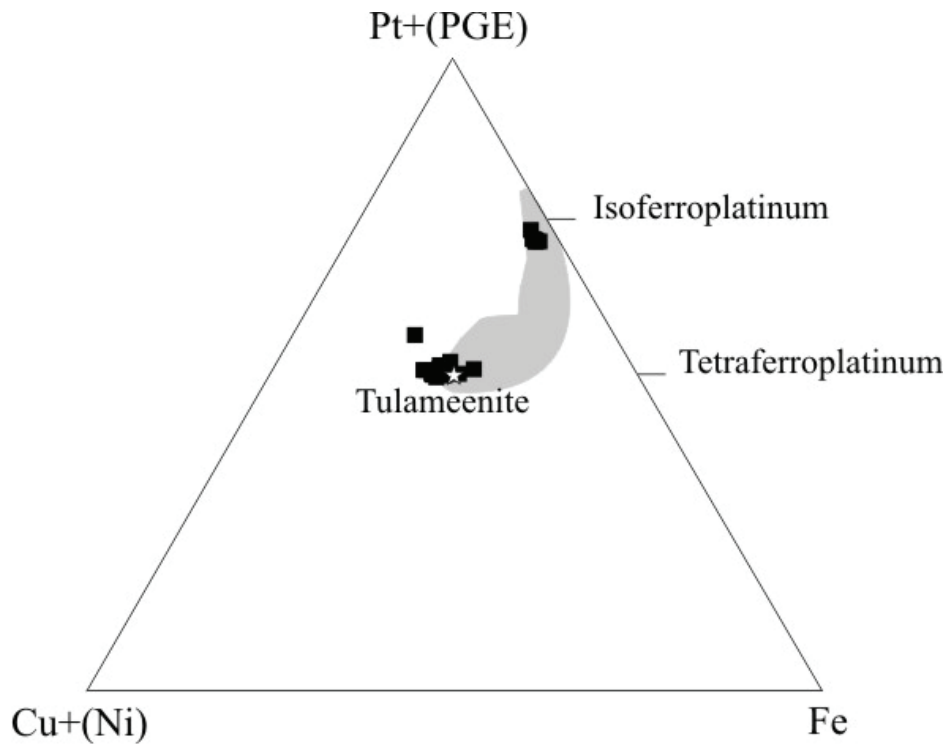

Figure 10. *Quantitative analyses of PGM within the Pt-Fe-Cu-Ni system (plotted as atomic %).*

DISCUSSION

Origin of Eikland Mountain chromitites

The Eikland Mountain chromitites have a chromian spinel composition and PGM content atypical of many mantle-hosted chromitites from orogenic mantle massifs or oceanic ophiolite complexes. According to recent genetic models of the formation of chromitites in these settings, chromitite hosted in mantle rock is due to the crystallization of chromian spinel in a magma produced by partial melting of a deep source, and percolating upwards through the residual upper mantle, along sub-vertical porous conduits and channels (Lago *et al.*, 1982; Leblanc and Ceuleneer, 1992; Zhou *et al.*, 1994; Braun and Kelemen, 2002). Chromium saturation in the up-streaming mafic melt is achieved due to: decrease of pressure and temperature; mixing between resident melts and successive magma pulses; and reaction between melt with the country-rock mantle peridotite (Irvine, 1977; Zhou *et al.*, 1994). Generally, dunite represents the metasomatic product of the interaction of melt with wall-rock harzburgite (Braun and Kelemen, 2002), generated by the breakdown of pyroxenes. Large, massive chromite ores can be generated this way if the system is kept within the stability field of chrome spinel for a long time (Irvine, 1977). This critical condition is controlled by many factors among which the large amount of percolating magma, and a high chemical gradient (disequilibrium) between melt and country rock play a fundamental role (Zhou and Robinson 1997). If the chemical gradient is small and equilibrium is rapidly achieved during mantle-melt interaction, the expected reaction would not be adequate to produce significant volumes of chromitite, and instead would yield disseminated chromite grains in cumulus dunite.

The small (as far as observed) size of chromitite bodies at Eikland Mountain leads us to assume that either one or both of the above critical conditions (volume of percolating melt and/or melt-rock chemical gradient) did not take place, or, that the exposures at Eikland Mountain are on the periphery of a more fully developed mineralizing system. If the former, we would infer that the chemical system was fluctuating between the chromite stability field and the chromite-olivine cotectic line, thereby generating relatively small veins of chromite within large pods/channels of disseminated chromite-bearing dunite, mostly formed by melt-rock reaction. Further exploration would be required to assess the latter possibility.

Any genetic model for the Eikland Mountain chromitite veins must take into account the following considerations: 1) the veins formed from low degrees of melts - alkaline liquids; 2) the veins occur within foliated dunite formed in zones of mantle shear but are syn-to-post kinematic regarding mantle deformation; and 3) the veins are spatially associated with geochemically primitive gabbro with trace-element systematics compatible with a nascent arc environment. Furthermore, the low-to-moderate Cr#, high TiO_2 and PPGE enrichment described in this study indicate that chromitite veins in Eikland Mountain formed from low degrees of melting and percolation of melts through the ultramafic rocks in localized channels related to high porosity/shearing deformation. Hence, evolved suprasubduction zone or fast-spreading-ridge settings are discarded as possible tectonic settings.

A slowly extending setting having low degrees of melting, in which incompatible element-rich melts reacted with harzburgite to produce high TiO_2 chromitites with alkaline-rich inclusions, is the most suitable environment of origin. The small volumes of rich alkaline melts were extracted from deep levels of the upwelling mantle at moderate to high oxygen fugacity (Mungall *et al.*, 2006) and were trapped in cracks reacting with host peridotite and consequently crystallized in the form of discordant Rh-Pt-Pd rich chromitite veins.

The spatial association of the chromitite veins with post-kinematic primitive arc-affinity gabbro dykes suggests that the extensional regime accompanied a phase of arc initiation. Although the age of the Eikland Mountain gabbro has not been determined, geochemically similar bodies on Koidern Mountain are *ca.* 274 Ma (*e.g.*, Murphy *et al.*, 2011; Escayola *et al.*, in prep.), only slightly predating the onset of westward subduction of the Slide Mountain terrane beneath the Yukon-Tanana terrane. In line with these considerations, we propose that the chromitite veins were formed in zones of enhanced permeability (inactive mantle shear zones) during the extensional arc-initiation phase of a late Permian magmatic arc built on both Slide Mountain and Yukon-Tanana terranes.

Discoveries of platinum group minerals (PGM) within numerous gold placer deposits in southwest Yukon are frequently reported to the Yukon Geological Survey (*e.g.*, Fedortchouk and LeBarge, 2008). The source rocks for these PGM have not been determined with certainty. EMP analyses of Pt-Fe alloys found in local placers by Fedortchouk *et al.* (2010) display elevated values of Pd (up to 5.84 mass%), Rh (up to 1.94 mass%) and Cu (up to 1.19 mass %). These authors propose an Alaskan type mineralization as the potential source for placer PGM. However, given the geochemical similarities between Eikland Mountain mineralization and the placer PGMs, we infer that the Eikland Mountain-style mineralization may have been the source for the placers. As PGMs are found in placers over a wide area in Yukon, Eikland Mountain-style mineralization may be (or may have been) more widespread than just at Eikland Mountain. The unusual Pt-Pd-rich chromitites from Eikland Mountain open a wide field of research and exploration in ultramafic complexes in southwest Yukon.

ACKNOWLEDGEMENTS

REFERENCES

Anonymous, 1972. Penrose field conference on ophiolites. Geotimes, vol. 17, p. 24–25.

Bodinier, J.-L. and Godard, M., 2003. Orogenic, ophiolitic, and abyssal peridotites. *In:* Treatise on Geochemistry, vol. 2: Mantle and Core, R.W. Carlson (ed.), Elsevier Science Ltd., p. 103-170.

Braun M.G. and Kelemen, P.B., 2002. Dunite distribution in the Oman ophiolite: Implications for melt flux through porous dunite conduits. Geochemistry, Geophysics, Geosystems, vol. 3, 8603, 21 p., doi: 10.1029/2001GC000289.

Canil, D. and Johnston, S.T., 2003. Harzburgite Peak: A large mantle tectonite massif in ophiolite from southwest Yukon. *In:* Yukon Exploration and Geology 2002, D.S. Emond and L.L. Lewis (eds.), Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, p. 77-84.

Cannat, M., Mével, C., Maia, M., Deplus, C., Durand, C., Gente, P., Agrinier, P., Belarouchi, A., Dubuisson, G., Humler, E., and Reynolds, J., 1995. Thin crust, ultramafic exposures, and rugged faulting patterns at the Mid-Atlantic Ridge (22°–24°N). Geology, vol. 23, p. 49-52, doi: 10.1130/0091-7613(1995)023<0049:TCUEAR>2.3.CO;2.

Colpron, M. and Nelson, J.L., 2011. A digital atlas of terranes for the Northern Cordillera. Accessed online from Yukon Geological Survey (www.geology.gov.yk.ca).

Colpron, M., Nelson, J.L., and Murphy, D.C., 2006. A tectonostratigraphic framework for the pericratonic terranes of the northern Canadian Cordillera. *In:* Paleozoic evolution and metallogeny of pericratonic terranes at the ancient Pacific margin of North America, Canadian and Alaskan Cordillera, M. Colpron, J.L. Nelson and R.I. Thompson (eds.), Geological Association of Canada Special Paper 45, p. 1-23.

Creaser, R.A., Goodwin-Bell, J.A.S., and Erdmer, P., 1999. Geochemical and Nd isotopic constraints for the origin of eclogite protoliths, northern Cordillera: implications for the Paleozoic tectonic evolution of the Yukon-Tanana terrane. Canadian Journal of Earth Sciences, vol. 36, p. 1697-1709.

Crockett, J. H., 2002. *In:* The Geology, geochemistry, Mineralogy and beneficiation of PGE, Cabri, L. J. (ed.), Canadian Institute of Mining, Metallurgy, and Petroleum Special Volume 54, p. 177-210.

Dick, H.J.B., 1989. Abyssal peridotites, very slow-spreading ridges and ocean ridge magmatism. *In*: Magmatism in the Ocean Basins, A.D. Saunders and M.J. Norris, (eds.), Geological Society of London Special Publication 42, p. 71-105.

Dick, H.J.B., Natland, J.H., and Ildefonse, B., 2006. Past and future impact of deep drilling in the oceanic crust and mantle: Oceanography (Washington, D.C.), vol. 19, p. 72-80.

Dickey, J.S., 1975. A hypothesis of origin for podiform chromite deposits. Geochimica et Cosmochimica Acta, vol. 39, p. 1061-1074.

Dusel-Bacon, C., Hopkins, M.J., Mortensen, J.K., Dashevsky, S.S., Bressler, J.R., and Day, W.C., 2006. Paleozoic tectonic and metallogenic evolution of the pericratonic rocks of east-central Alaska and adjacent Yukon. *In:* Paleozoic Evolution and Metallogeny of Pericratonic Terranes at the Ancient Pacific Margin of North America, Canadian and Alaskan Cordillera, M. Colpron and J.L. Nelson (eds.), Geological Association of Canada, Special Paper 45, p. 25-74.

Escayola, M., Murphy, D.C., Proenza, J., van Staal, C., McClelland, W., and Friedman, R., (in prep.). Western Yukon ultramafic complexes, an example of a slow spreading ridge segment in the Permian Slide Mountain Ocean: Geochemistry, U-Pb geochronology and Sm-Nd isotopic analyses.

Fedortchouk, Y. and LeBarge, W., 2008. Sources of placer platinum in Yukon: provenance study from detrital minerals. Canadian Journal of Earth Sciences, vol. 45, p. 879-896.

Fedortchouk, Y., LeBarge, W., Barkov, A., Fedele, L., Bodnar, R.J., and Martin, R.F., 2010. Platinum-group minerals from a placer deposit in Burwash Creek, Kluane area, Yukon Territory, Canada. The Canadian Mineralogist, vol. 48, p. 583-596.

Garuti, G., Oddone, M., and Torres Ruiz, J., 1997a. Platinum-group-element distribution in subcontinental mantle: evidence from the Ivrea Zone (Italy) and the Betic-Rifean Cordillera (Spain and Morocco). Canadian Journal of Earth Sciences, vol. 34, p. 444-463.

Garuti, G., Fershataer, G., Bea, F., Montero, P., Pushkarev, E.V., and Zaccarini, F., 1997b. Platinum-group elements as petrological indicators in mafic-ultramafic complexes of the central and southern Urals: preliminary results. Tectonophysics, vol. 276, p. 181-194.

Garuti, G., Pushkarev, E.V., Zaccarini, F., Cabella, R., Anikina, E., 2003. Chromite composition and platinum-group mineral assemblage in the Uktus Uralian-Alaskan-type complex (Central Urals, Russia). Mineralium Deposita, vol. 38, p. 312-326.

Irvine, T.N., 1977. Origin of chromite layers in the Muskox intrusion and other stratiform intrusions. A new interpretation. Geology, vol. 5, p. 273-277.

Kelemen, P.B. and Dick, H.J.B., 1995. Focused melt flow and localized deformation in the upper mantle: juxtaposition of replacive dunite and ductile shear zones. Journal of Geophysical Research, vol. 100, p. 423-438.

Lago, B.L., Rabinowicz, M., and Nicolas, A., 1982. Podiform chromite ore bodies: a genetic model. Journal of Petrology, vol. 23, p. 103-125.

Leblanc, M. and Ceuleneer, G., 1992. Chromite crystallization in a multicellular magma flow: Evidence from a chromitite dike in the Oman ophiolite. Lithos, vol. 27, p. 231-257.

Mungall, J.E., Hanley, J.J, Arndt, N.T., and Debecdelievre, A., 2006. Evidence from meimechites and other low-degree mantle melts for redox controls on mantle-crust fractionation of platinum-group elements. Geology, vol. 103, p. 12695-12700.

Murphy, D.C., van Staal, C., and Mortensen, J.K., 2008. 'Windy-McKinley' terrane, Stevenson Ridge area (115JK), western Yukon: composition and proposed correlations, with implications for mineral potential. *In:* Yukon Exploration and Geology 2007, D.S. Emond, L.R. Blackburn, R.P. Hill and L.H. Weston (eds.), Yukon Geological Survey, p. 225-235.

Murphy, D.C., Mortensen, J.K., and van Staal, C., 2009. 'Windy-McKinley' terrane, western Yukon: new data bearing on its composition, age, correlation and paleotectonic settings. *In:* Yukon Exploration and Geology 2008, L.H. Weston, L.R. Blackburn and L.L. Lewis (eds.), Yukon Geological Survey, p. 195-209.

Murphy, D.C., 2011. New mineral exploration opportunities highlighted by new geoscience data, Stevenson Ridge and northern Kluane Lake areas, southwestern Yukon. Mineral Exploration Roundup 2011, poster presentation, available at www.geology.gov.yk.ca.

Murphy, D.C., Escayola, M., van Staal, C., Friedman, R., McLelland, W., and Mortensen, J.K., 2011. Ophiolitic complexes of western Yukon: age, geochemical character, geological setting, terrane correlation and metallogeny. Yukon Geoscience Forum, poster presentation, available at www.geology.gov.yk.ca.

Naldrett, A.J., Kinnaird, A., Wilson, A., Yudovskaya, M., McQuade, S., Chunnett, G., and Stanley, C., 2009. Chromite composition and PGE content of Bushveld chromitites: Part 1 – the Lower and Middle Groups. Applied Earth Science: IMM Transactions section B, vol. 118, no. 3-4, p.131-161.

Nelson, J.L., 1993. The Sylvester allochthon: Upper Paleozoic marginal-basin and island-arc terranes in northern British Columbia: Canadian Journal of Earth Sciences, vol. 30, p. 631-643.

Prichard , H.M., Load, R.A., and Neary, C.R., 1996. A model to explain the occurrence of platinum and palladium-rich ophiolite complexes. Journal of the Geological Society London, vol. 153, p. 323-328.

Prichard, H.M., Neary, C.R., Fisher, P.C., and O'Hara, M.J., 2008. PGE-rich Podiform Chromitites in the Al'Ays Ophiolite Complex, Saudi Arabia: An Example of Critical Mantle Melting to Extract and Concentrate PGE. Economic Geology, vol. 103, p. 15071529.

Rudashevsky, N.S. and Rudashevsky, V.N., 2001. Method for separating granular material and device for carrying out said method. Russian patent #2165300. M. 2001.

Rudashevsky, N.S. and Rudashevsky, V.N., 2006. Hydraulic classifier. Russian patent. Invention No. 2281808. M. 2006.

Rudashevsky, N.S. and Rudashevsky V.N., 2007. Device for separation of solid particles. Application for Russian patent #2007121079. Date of priority 06.06.2007.

Torres-Ruiz, J., Garuti, G., Gazzotti, M., Gervilla, F., and Fenoll hach-Alí, P., 1996. Platinum-group minerals in chromitites from the Ojen lherzolite massif (Serranía de Ronda, Betic Cordillera, Southern Spain). Mineralogy and Petrology, vol. 56, p. 25-50.

Zhou, M.F., Robinson, P.T., and Bai, W.J., 1994. Formation of podiform chromitites by melt/rock interaction in the upper mantle. Mineralium Deposita, vol. 29, p. 98-101.

Zhou, M.F. and Robinson, P.T, 1997. Origin and tectonic environment of podiform chromite deposits. Economic Geology, vol. 92, p.98-101.