GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7856

Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models

Hybridized ultramafic rocks in the Black Label hybrid zone of the Black Thor intrusive complex, McFaulds Lake greenstone belt, Ontario

Charles S. Spath III[1], C. Michael Lesher[1], and Michel G. Houlé[2]

[1]Laurentian University, Sudbury, Ontario
[2]Geological Survey of Canada, Québec, Quebec

2015

Recommended citation

Spath, C.S. III, Lesher, C.M., and Houlé, M.G., 2015. Hybridized ultramafic rocks in the Black Label hybrid zone of the Black Thor intrusive complex, McFaulds Lake greenstone belt, Ontario, *In:* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models, (ed.) D.E. Ames and M.G. Houlé; Geological Survey of Canada, Open File 7856, p. 103–114.

Publications in this series have not been edited; they are released as submitted by the author.

Contribution to the Geological Survey of Canada's Targeted Geoscience Initiative 4 (TGI-4) Program (2010–2015)

TABLE OF CONTENTS

Hybridized ultramafic rocks in the Black Label hybrid zone of the Black Thor intrusive complex, McFaulds Lake greenstone belt, Ontario

Charles S. Spath III[1]*, C. Michael Lesher[1], Michel G. Houlé[2]

[1]Mineral Exploration Research Centre, Department of Earth Sciences, Goodman School of Mines, Laurentian University, 935 Ramsey Lake Road, Sudbury, Ontario P3E 2C6
[2]Geological Survey of Canada, 490 rue de la Couronne, Québec, Quebec G1K 9A9
*Corresponding author's e-mail: CSpath@laurentian.ca

ABSTRACT

The ca. 2.7 Ga Black Thor intrusive complex (BTIC) is an ultramafic to mafic, layered intrusion composed primarily of dunite, peridotite, pyroxenite, and chromitite overlain by lesser gabbroic rocks and rare anorthosite. After emplacement but before complete crystallization, a late websterite intrusion (LWI) reactivated the feeder conduit and transected the basal part of the BTIC, including the Black Label chromitite zone (BLCZ). All rocks have been metamorphosed to lower greenschist facies, but igneous minerals are preserved in some parts (particularly in the LWI) and relict igneous textures are well preserved in most parts. Logging of selected parts of 39 drill cores shows that semi-concordant intrusion of LWI magma and incorporation of inclusions produced a 1 to 10 m thick marginal zone of heterogeneous, interfingering breccia-tion defined as the Black Label hybrid zone (BLHZ). The BLHZ contains variably sized (1–50 cm) dunite/lherzolite/ chromitite inclusions with subangular to amoeboidal geometries, sharp to diffuse contacts, and locally significant amounts of patchy disseminated to patchy net-textured Fe-Ni-Cu-(PGE) sulphide mineralization. The core of the LWI is typically an inclusion-free, medium-grained, orthopyroxene-rich adcumulate with accessory chromite or olivine; however, inclusion-rich intervals of the LWI contain more olivine and chromite produced by disaggregation and partial assimilation of BTIC ultramafic rocks. There are two types of hybrid groundmass: one containing xenocrystic olivine and one containing xenocrystic chromite and olivine in varying proportions. Geochemical signatures of the hybrid rocks reflect the partial assimilation and brecciation of chromitite/lherzolite/dunite sequences. Similar Th-U-Nb-Ta-light rare earth element LREE patterns suggest that the LWI is related to the BTIC, presumably representing a more fractionated magma from deeper in the system. Further characterization of the hybrid rocks and inclusion variability is in progress and will help to establish the range and variability of processes within the BTIC, and their influence on the genesis of associated Fe-Ni-Cu-PGE sulphide mineralization in the BLHZ.

INTRODUCTION

The ca. 2.7 Ga Black Thor intrusive complex (BTIC) is a funnel-shaped, semi-conformable, layered intrusion composed primarily of dunite, lherzolite, olivine websterite, websterite, and chromitite overlain by lesser melagabbro to leucogabbro, and rare anorthosite. It is part of the "Ring of Fire" intrusive suite (RoFIS) located within the McFaulds Lake greenstone belt (MLGB) in the Oxford-Stull domain, James Bay Lowlands of northern Ontario. After emplacement and before complete crystallization of the BTIC, a late websterite intrusion (LWI) transgressed the semi-consolidated lower and middle ultramafic parts of the complex, including the Black Label chromitite zone (BLCZ), producing a variety of breccia and hybrid rock types, referred to as the Black Label hybrid zone (BLHZ). The BLHZ contains variably sized (1–50 cm) dunite/lherzolite/chromitite inclusions with subangular to amoeboidal geometries and sharp to diffuse contacts. The BLHZ is localized in marginal zones and in discrete pods within the LWI, and is locally associated with synmagmatic patchy disseminated to patchy net-textured Fe-Ni-Cu-(PGE) sulphide mineralization.

The objectives of this project are to (1) characterize all rock types and lithofacies associated with the BLHZ, including the ultramafic precursors of the BTIC and the LWI; (2) establish the textural variability of the inclusions (e.g. heterolithic versus homolithic compositions, rounded versus subangular forms, sharp versus diffuse contacts); and (3) constrain the mechanism(s) of emplacement and hybridization. The purpose of this contribution is to present the main objectives, research

Spath, C.S. III, Lesher, C.M., and Houlé, M.G., 2015. Hybridized ultramafic rocks in the Black Label hybrid zone of the Black Thor intrusive complex, McFaulds Lake greenstone belt, Ontario, *In:* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models, (ed.) D.E. Ames and M.G. Houlé; Geological Survey of Canada, Open File 7856, p. 103–114.

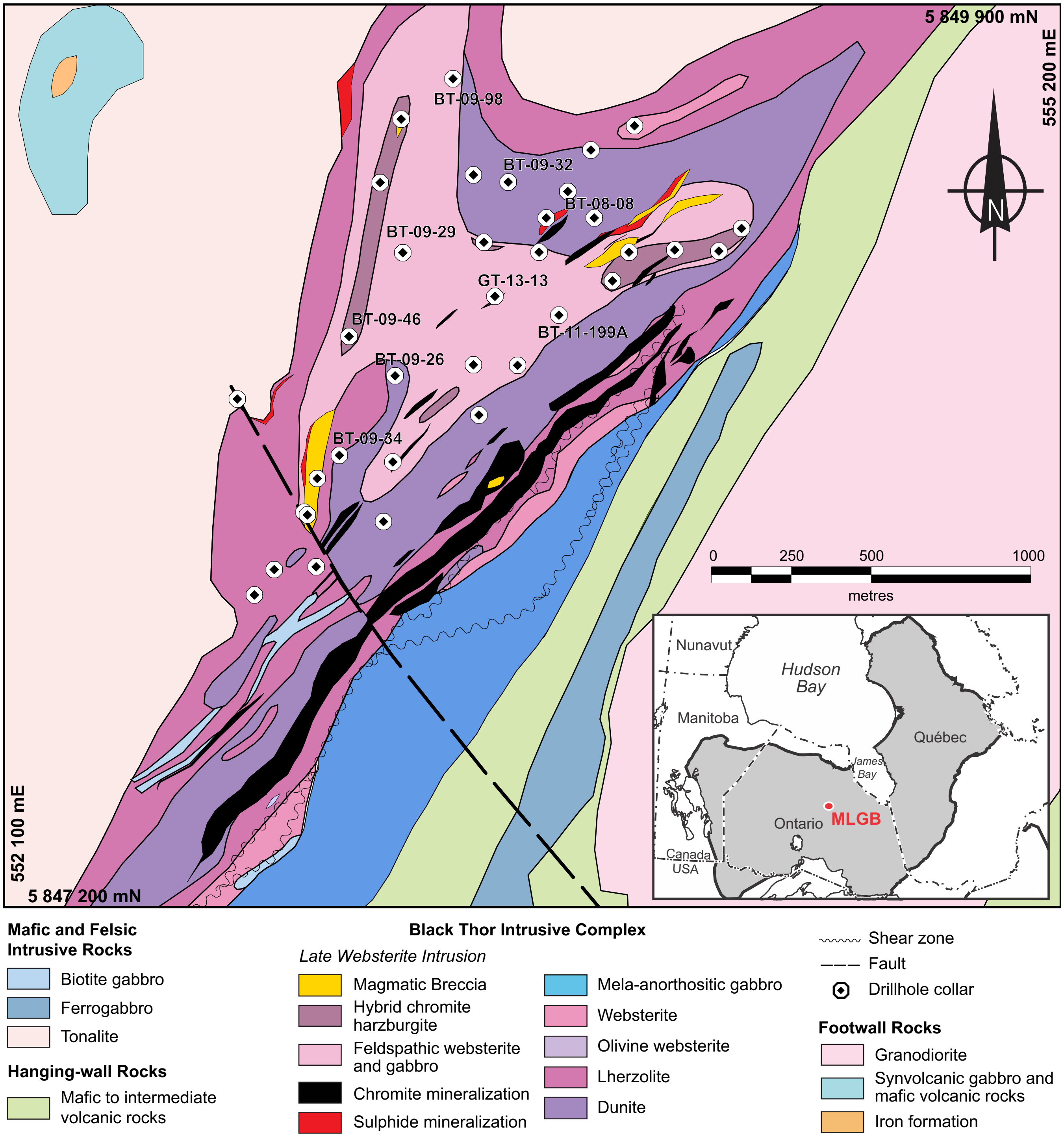

Figure 1. Simplified geological map at 100 m depth showing the locations of diamond drillholes that were logged and sampled in the course of this study (modified from Weston and Shinkle, 2013). Abbreviation: MLGB = McFaulds Lake greenstone belt.

methods, preliminary results, and some exploration implications of an M.Sc. project undertaken by the senior author at Laurentian University under the supervision of Drs. Lesher and Houlé.

METHODOLOGY

Fieldwork for this project was completed in June and July 2013 at the Cliffs Natural Resources "Esker Camp" in the James Bay Lowland. Detailed core logging was conducted to record rock types and textural variations within each rock unit (LWI, BLHZ, BTIC, BLCZ) and to collect homogeneous representative samples for petrographic study, mineral analyses, and whole-rock geochemical analyses. Selected parts of 39 drill cores (Fig. 1) were re-logged, from which 314 representative samples were taken including 123 samples of the LWI websterite, 19 samples of LWI feldspathic websterite and gabbro, 139 samples of the BLHZ rocks, 10 samples of BTIC dunite and peridotite, and 23 samples of the BLCZ. Thus far, 150 representative NQ core samples (48 mm in diameter) have been halved, ground to remove saw marks, scanned, and examined using binocular microscopy to establish relevant mesoscopic textures. One hundred and twenty-four of these samples were examined in thin section (81 standard polished, 17 standard, 21 large, and 5 extra-large thin sections) using transmitted and reflected light to establish mineralogy and microscopic textures relevant to the petrogenesis of the BLHZ, and also to select representative least altered samples for whole-rock geochemistry. Thirty-three samples have been analyzed thus far for major, minor, and trace elements by a combination of wavelength dispersive X-ray fluorescence spectrometry (WDS-XRFS) and inductively coupled plasma mass spectrometry (ICP-MS) at the Ontario Geoscience Laboratories in Sudbury. Results for another 55 samples are pending. The data received have been interpreted in combination with data collected by Carson et al. (2015). Five polished thin sections have been studied/analyzed using a scanning electron microscope (SEM) and energy dispersive-X-ray emission spectrometry (ED-XRES) methods to establish the nature of zoning of silicate and oxide minerals associated with the BLHZ. Twelve polished thin sections (399 total spots) have been analyzed using an electron probe micro-analyzer (EPMA) and wavelength dispersive XRES methods to determine the compositions of relict pyroxene, olivine, plagioclase, and chromite.

RESULTS

Geology and Petrography of the Late Websterite Intrusion

The late websterite intrusion (LWI) is defined as a distinct intrusion comprising websterite, feldspathic websterite, and gabbro that transgresses the basal portions of the BTIC, which is spatially, texturally, mineralogically, and genetically different from websterite present in the upper parts of the BTIC. It is distinguished from BTIC pyroxenite by (1) a much greyer colour; (2) a low degree of alteration; (3) the presence of much more orthopyroxene, which is characterized by an adcumulate texture; (4) abundant inclusions in the parts bordering the earlier phases of the BTIC; and (5) restriction to the lower 2/3 of the BTIC. The LWI is ~1.8 km long and ~1 km thick and has been intersected in drill core in the feeder, basal, and central parts of the BTIC (Fig. 1).

Websterite

The dominant rock type in the LWI, which composes ~85% of the intrusion, is an orthopyroxene-rich, pinkish grey, generally medium-grained, meso- to adcumulate websterite with varying proportions of pyroxene (95:5 to 80:20 orthopyroxene:clinopyroxene) with lesser plagioclase (up to 10 modal%; An_{77}), accessory chromite and olivine (Figs. 2a and 3a). Orthopyroxene is always a cumulus phase, clinopyroxene is most commonly an intercumulus phase, and feldspar is almost always an intercumulus phase. The late websterite is crosscut by gabbroic dykes and sulphide/magnetite/talc-serpentine veinlets, but remains relatively unaltered. However, both pyroxene and olivine contained within the inclusion-rich phases of the LWI are more commonly serpentinized or amphibolitized.

Feldspathic Websterite and Gabbro

Feldspathic websterite and gabbro that compose 15% of the LWI occur most commonly in the central portion of the LWI and contain no inclusions. These rocks appear to represent the residual liquid of the crystallizing LWI cumulates. The LWI feldspathic websterite and LWI gabbro are enriched in Al-Ca-P-K-Ti-Sr-Zr-REE and other incompatible lithophile elements, are depleted in Mg-Fe, and have higher abundances of plagioclase (up to 60 modal%; ~An_{85}) and clinopyroxene relative to LWI websterite (Fig. 3b). Late websterite intrusion feldspathic websterite and LWI gabbro comprise three varieties, all of which are blue-grey and coarse-grained to pegmatitic: 1) orthocumulate feldspathic websterite, which occurs in small (5–50 cm) stringers within websterite (Fig. 2b); 2) melagabbro; and 3) rare meso-leucogabbro, which occurs in both large (0.5–5 m) discrete pods, and crosscutting pegmatitic dykes (5–30 cm), respectively. Fe-Ni-Cu-(PGE) sulphide (5–10%) mineralization is present as small blebs along the margins of small pods and dykes of meso-leucogabbro that transgress BTIC lithologies and LWI websterite.

Geology and Petrography of the Black Label Hybrid Zone

The LWI is transgressive to layering in the lower parts of the BTIC, but semi-concordant along the lateral margins, especially in the BLCZ, where fine, distinct olivine- and chromite-rich bedding exists. The amoeboidal shapes of some of the chromite inclusions suggest that the Black Label hybrid zone (BLHZ) formed by injection of the late websterite melt into semi-consolidated dunite-lherzolite-chromitite horizons of the BTIC. Within inclusion-rich intervals, interclastic groundmass has been locally hybridized through the disaggregation of partially consolidated ultramafic intervals (i.e. incorporation of xenocrystic olivine and chromite; Fig. 2c,d). Black Label hybrid zone intervals are localized in marginal zones (1–10s m thick) and in discrete pods (1–15 m) and within the LWI. Websterite

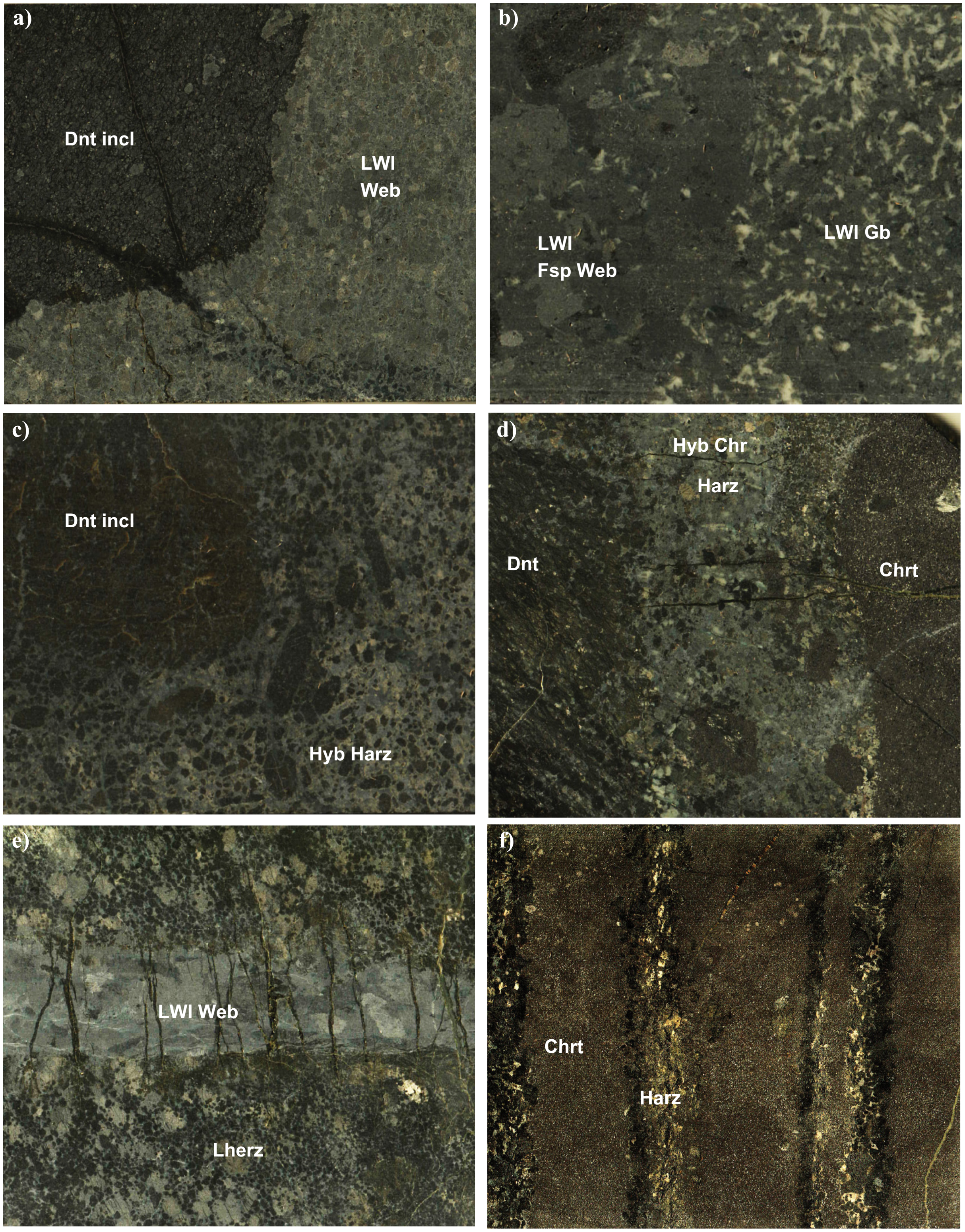

Figure 2. Representative scans of NQ (48 mm diameter) and HQ (64 mm diameter) drill core (younging direction to the right). **a)** Dunite inclusion (Dnt incl) contained within the late websterite intrusion (LWI Web); note vein of alteration (serpentinization and amphibolization), sample BT-11-199A/34.2 m, HQ core. **b)** Pegmatitic LWI feldspathic websterite (LWI Fsp Web) with more evolved LWI gabbro (LWI Gb) at right, sample BT-09-98/211.4 m, NQ core. **c)** Dunite inclusion (Dnt inc) within hybrid harzburgite (Hyb Harz); note the bimodal xenocrystic olivine, sample BT-09-46/212 m, NQ core. **d)** Concordant injection of late websterite (now hybrid chromite harzburgite: Hyb Chrt Harz) between chromitite (Chrt) and dunite (Dnt) beds, focusing disaggregation; note the presence of smaller (<1 cm) inclusions and xenocrysts, sample GT-13-13/251.3 m, HQ core. **e)** BTIC lherzolite (Lherz) discordantly injected by late websterite (LWI Web), note crosscutting serpentinite veinlets, sample GT-13-13/43.5 m, HQ core. **f)** Bedded chromitite (Chrt) with alternating massive chromite-harzburgite (Harz) intervals, sample GT-13-13/247.5 m, HQ core.

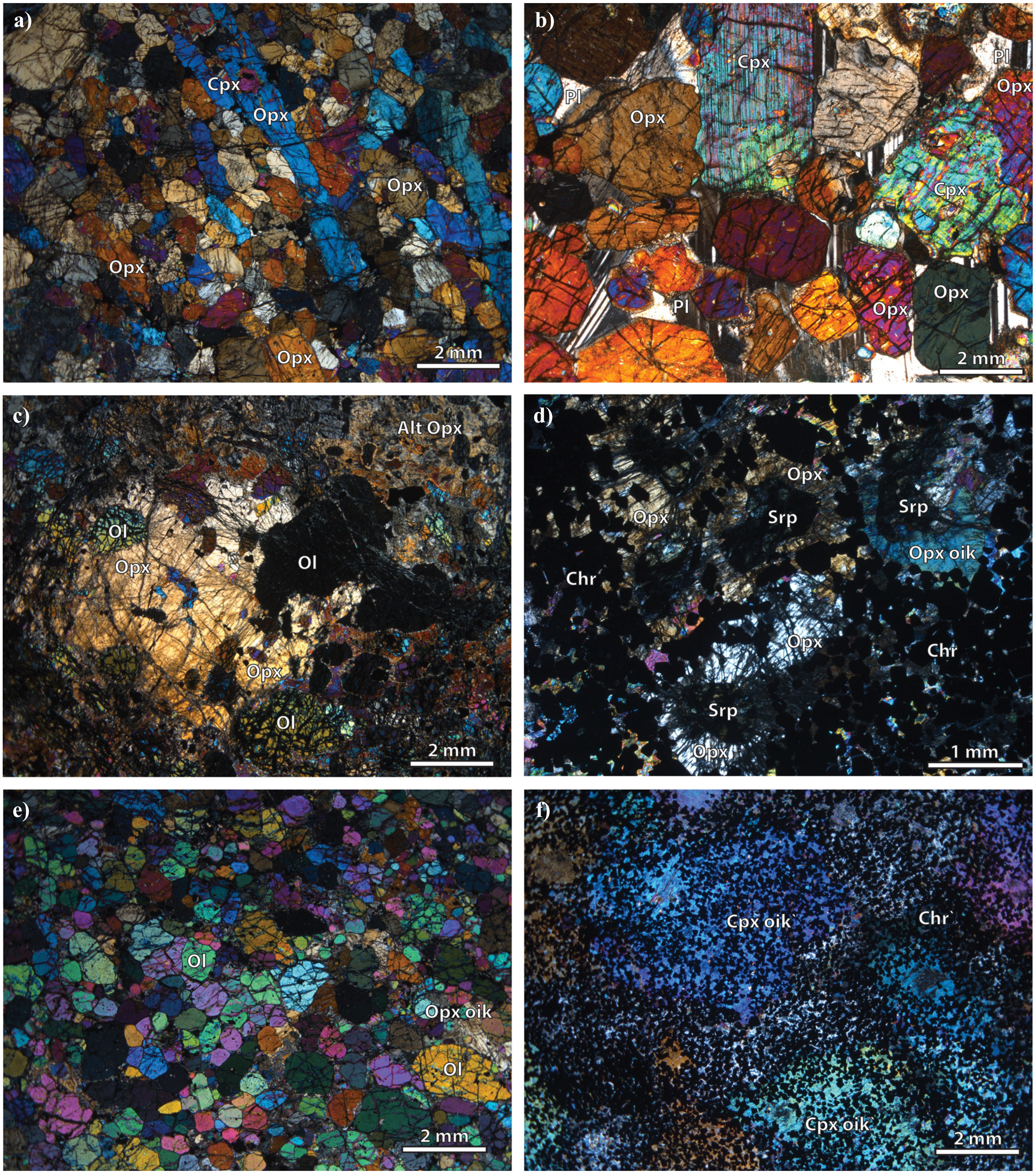

Figure 3. Photomicrographs of representative polished thin sections in cross-polarized light. **a)** Adcumulate late websterite intrusion (LWI) with a hypidiomorphic texture; note clinopyroxene (Cpx) oikocryst (oik) and atypical elongate crystals of orthopyroxene (Opx), sample BT-09-98 @ 249 m. **b)** Heteradcumulate LWI feldspathic websterite with oikocrystic plagioclase (Pl) and both euhedral clinopyroxene and orthopyroxene, sample BT-09-34 @ 120.5 m. **c)** Poikilitic hybrid harzburgite adjacent to dunite inclusion (lower right); note blebby olivine (Ol) with corroded margins and altered orthopyroxene (Alt Opx), sample BT-09-98 @ 361 m. **d)** Heteradcumulate hybrid chromite harzburgite; note blebby, irregular serpentinized olivine (Srp) enclosed with orthopyroxene that is devoid of chromite (Chr), sample BT-09-29 @ 313.7 m. **e)** Adcumulate dunite with inequigranular and panidiomorphic texture, sample BT-09-32 @ 129 m. **f)** Net-textured chromitite, with oikocrystic clinopyroxene (Cpx oik) enveloping fine-grained chromite between oikocrysts chromite, is locally more abundant giving a patchy texture, sample BT-08-08 @ 217 m.

that contains inclusions, *but* not hybrid groundmass, is considered part of the LWI; whereas websterite that has a locally hybridized matrix and/or inclusions is considered part of the BLHZ. The greater abundance of xenocrystic olivine and inclusions in the BLHZ results in a more pervasive alteration signature than in the LWI.

Hybrid Harzburgite

The most abundant hybrid rock type is localized in dunite-lherzolite inclusion-rich intervals and comprises varying proportions of orthopyroxene (40–70%), olivine (5–50%), and clinopyroxene (5–20%). Accessory chromite, plagioclase, and sulphide are present, with some intervals containing up to 10% disseminated to patchy net-textured Fe-Ni-Cu-(PGE) sulphides. Olivine is a cumulus phase and ranges from 2 to 9 mm in diameter (Fig. 3c). It is localized along inclusion margins and appears to have been produced by disaggregation of lherzolite and dunite inclusions. The abundance of olivine varies, forming olivine websterite or harzburgite. Orthopyroxene is euhedral and a cumulus phase, but when present with olivine exhibits an oikocrystic texture. Olivine xenocrysts are corroded along the margins and blebby and irregular in shape within orthopyroxene oikocrysts (derived from LWI melt) (Fig. 3c). Clinopyroxene is an anhedral intercumulus phase. Distinguishing between rock types at a map-scale is difficult, as they vary on the decimetre to metre scale within the BLHZ, thus for simplicity this component is termed the “hybrid harzburgite”.

Hybrid Chromite Harzburgite

This rock type is less abundant and occurs in brecciated BLCZ intervals; it comprises varying proportions of orthopyroxene (20–70%), olivine (5–40%), chromite (10–40%), and clinopyroxene (5–20%). Accessory plagioclase and sulphide are present, with some intervals containing up to 10% disseminated to patchy net-textured Fe-Ni-Cu-(PGE) sulphides. Olivine, orthopyroxene, and clinopyroxene exhibit the same textures as in hybrid harzburgite, but are fine- to very fine-grained; euhedral chromite chadacrysts exhibit no corrosive features and were apparently refractory during hybridization.

Textural relationships in heavily disseminated to net-textured chromite harzburgite (10–50% chromite) indicate selective replacement of olivine by orthopyroxene, where the margins of originally larger olivine grains have been replaced by orthopyroxene, leaving smaller corroded olivine surrounded by chromite-free halos (Fig. 3c). Olivine and chromite xenocrysts are localized around inclusion margins and therefore are interpreted to represent disaggregation of banded chromitite-dunite and heavily disseminated to semi-massive chromitite. The abundance of olivine varies, forming chromite websterite, chromite olivine-websterite, or chromite harzburgite. Similar to the hybrid harzburgite, distinguishing between rock types on a map-scale is difficult, so for simplicity this component is termed the “hybrid chromite harzburgite”.

Ni-Cu-(PGE) Mineralization

Significant sulphide mineralization is present in the SW breccia, Central breccia, and NE breccia zones of the BLHZ (Farhangi et al., 2013) and always occurs interstitially to the silicate and oxide constituents of the BLHZ, indicating that it formed during the hybridization process. It forms low interfacial angles (15–70°) with olivine and chromite, indicating that it “wetted” olivine, but high interfacial angles (65–105°) with pyroxene, indicating that it did not wet pyroxene, resulting in patchy disseminated to patchy net textures.

Inclusion Variability

Inclusions are ubiquitous in the BLHZ and in the adjacent LWI (within ~5 m), and range from homo- to heterolithic (Table 1). The Black Label hybrid zone typically contains 10 to 50% inclusions, whereas the adjacent LWI websterite contains 5 to 10% inclusions. Only the core of the LWI contains extensive (>100 m) inclusion-free intervals. Inclusions vary in geometry (subangular to amoeboidal), contact style (sharp to diffuse), and size (1–50 cm, rarely >1 m). The lithological variability of the inclusions depends on the scale of layering in adjacent BTIC intervals: heterolithic inclusions occur adjacent to thinly layered chromitite-dunite intervals, whereas homolithic inclusions are more abundant adjacent to more thickly layered chromite-dunite intervals. Inclusion geometries vary systematically in the LWI. Subangular to subrounded inclusions are dominant along the basal contact, and rounded to amoeboidal inclusions are dominant in the core and upper margin of the LWI. The size of inclusions and the sharpness of their contacts vary, but show no regular distribution.

Mineral Chemistry

Major and selected minor-element compositions of the olivine, pyroxene, plagioclase, and chromite minerals in the LWI, adjacent BTIC, and BTIC inclusions are presented in Table 2.

Olivine compositions determined from the LWI, BLHZ, and BTIC are Fo_{75-70}, Fo_{81-76}, and Fo_{85-78}, respectively. It is apparent from trends in MgO variation plots of dunite-lherzolite that the most magnesian olivine in the BTIC is not represented in the suite of samples analysed so far, which is expected given that the analyzed samples were in the central, more evolved part of the BTIC and not in the lower, most primitive part (Fig. 4a).

Table 1. Petrographic features of the main types of inclusions in the Black Thor intrusive complex.

Lithology	Colour	Chromite (modal %)	Texture	Grain Size	Mineralogy	Description
Dunite	dark grey, green	0-10%	Oac	fg-cg	Ol (90-98%)-Opx-Chr	Cumulus Ol±Chr with intercumulus Opx; fg-mg Ol but rarely cg (up to 9 mm), fg-mg Opx, and vfg-fg Chr (Fig. 2a,c, 3e); most common inclusion in BLHZ and typically exhibits less angular shapes than chromite inclusions
Lherzolite	dark grey-green	0-10%	Omc to Ooc	fg-cg	Ol (75-90%) Opx (10-20%) -Cpx-Chr	Cumulus Ol and Chr with intercumulus Opx/Cpx; fg-mg Ol, mg-cg Opx; locally oikocrystic lherzolite with >30% cg lensoidal Opx (Fig. 2e)
Heavily disseminated to net-textured chromitite	dark grey-green	10-50%	OChac to OCoc	bi	1) Chr-Ol/Opx 2) Chr-Cpx± Ol/Opx	Ol, Chr, Opx cumulus with Cpx intercumulus; fg Chr, mg Ol and Opx, and cg-vcg Cpx; refractory chromitite inclusions typically exhibits more angular shapes. Chr occurs either: 1) locally within interstices of cumulus Ol and/or Opx (i.e. chain-texture); 2) patchy disseminated within oikocrystic Cpx with minor cumulus Ol/Opx (Fig. 3f)
Matrix & semimassive chromitite	dark grey	50-90%	OChac to OCoc	bi	1) Chr-Ol/Opx 2) Chr-Cpx± Ol/Opx	Same description as heavy disseminated to net-textured Chr; most common chromitite inclusion in BLHZ
Massive chromitite	black	90-98%	OChac	vfg-fg	Chr±(Ol/ Opx/Cpx)	Cumulus Chr, with minor cumulus Ol, Opx, and intercumulus Cpx; fg Chr, mg Ol and Opx, and cg-vcg Cpx; Massive chromitite occurs with either: a) round aggregates of Ol/Opx; b) mono- to polymineralic layering (<1 cm thickness) of Ol/Opx (Fig. 2f); c) negligible intercumulus Cpx phase

Minerals: Chr = chromite; Cpx = clinopyroxene; Ol = olivine; Opx = orthopyroxene; Pl = plagioclase. Cumulate phase: O, C = olivine, chromite, respectively

Cumulate texture: ac = adcumulate; hac = heteradcumulate; mc = mesocumulate; oc = orthocumulate. Grain size: vfg, fg, mg, cg, vcg = very fine- fine-, medium-, coarse-, very coarse-grained; bi = bimodal.

Table 2. Representative results of electron microanalyses of minerals from the late websterite intrusion (LWI), Black Label hybrid zone (BLHZ), and Black Thor intrusive complex (BTIC) inclusions within the BLHZ.

	LWI Websterite				**LWI Gabbro**			**BLHZ Harzburgite**			**BLHZ Chromite Harzburgite**				**BTIC Chromitite Inclusion**				**BTIC Dunite Inclusion**	
	Ol	Opx	Cpx	Pl	Opx	Cpx	Pl	Ol	Opx	Cpx	Chr	Ol	Opx	Cpx	Chr	Ol	Opx	Cpx	Ol	Opx
SiO_2	38.8	55.5	52.0	49.4	55.6	52.4	47.1	39.5	55.9	52.7	0.11	40.0	54.9	52.2	<0.01	40.5	56.2	53.2	40.4	55.5
TiO_2	<0.01	0.05	0.24	0.03	0.07	0.39	0.02	<0.01	0.09	0.22	0.89	<0.01	0.10	0.22	0.8	<0.01	0.08	0.14	<0.01	0.06
Al_2O_3	<0.01	1.13	2.83	31.8	1.50	2.30	33.3	<0.01	1.53	2.69	17.6	<0.01	1.64	2.69	15.9	0.01	1.59	1.99	<0.01	2.12
V_2O_3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.23	N/A	N/A	N/A	0.2	N/A	N/A	N/A	N/A	N/A
Cr_2O_3	<0.01	0.28	0.89	N/A	0.46	0.63	N/A	0.01	0.41	0.90	41.0	<0.01	0.46	1.05	45.7	0.02	0.57	1.07	0.02	0.75
Fe_2O_3	N/A	N/A	N/A	0.24	N/A	N/A	0.06	N/A	N/A	N/A	8.64	N/A	N/A	N/A	6.85	N/A	N/A	N/A	N/A	N/A
FeO	20.4	12.4	5.46	0.22	9.92	4.47	0.06	14.0	9.45	4.16	24.8	13.7	10.3	4.57	20.2	11.7	8.19	3.18	13.0	8.63
MnO	0.27	0.28	0.17	<0.01	0.24	0.15	0.02	0.23	0.25	0.15	0.33	0.21	0.25	0.16	0.3	0.18	0.22	0.11	0.21	0.22
CoO	0.03	0.01	0.01	N/A	0.02	0.01	N/A	0.03	0.01	0.01	0.03	0.02	<0.01	<0.01	0.03	0.03	0.01	<0.01	0.02	0.01
NiO	0.22	0.06	0.03	N/A	0.07	0.03	N/A	0.19	0.05	0.03	0.03	0.17	0.05	0.02	0.04	0.27	0.06	0.03	0.26	0.06
ZnO	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.09	N/A	N/A	N/A	0.07	N/A	N/A	N/A	N/A	N/A
MgO	40.5	29.8	15.9	0.01	31.3	16.4	0.01	44.6	31.4	16.4	6.96	45.7	30.7	16.8	9.43	47.7	32.2	17.5	46.5	31.1
CaO	0.03	0.65	22.0	15.0	0.85	22.4	17.0	0.02	1.00	22.5	N/A	0.02	1.29	22.0	N/A	0.03	1.41	22.3	0.01	1.98
SrO	N/A	N/A	N/A	0.01	N/A	N/A	<0.01	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Na_2O	<0.01	0.01	0.39	3.12	0.01	0.36	1.94	<0.01	0.03	0.41	N/A	<0.01	0.01	0.3	N/A	<0.01	0.03	0.31	<0.01	0.03
K_2O	<0.01	<0.01	0.01	0.02	<0.01	<0.01	0.01	<0.01	0.01	<0.01	N/A	<0.01	<0.01	<0.01	N/A	<0.01	<0.01	<0.01	<0.01	<0.01
Total	100.26	100.13	99.98	99.54	100.1	99.53	99.52	99.3	100.1	100.12	99.82	99.73	99.73	99.93	99.57	100.41	100.48	99.82	100.28	100.42

Abbreviations are same as Table 1; N/A = not analyzed. Sample locations: LWI Websterite from BT-11-180/171 m; LWI Gabbro from BT-09-32/119 m; BLHZ Harzburgite from BT-11-179/86.7 m; BLHZ Chromite Harzburgite from BT-11-177/107.6 m; BTIC Chromitite Inclusion from BT-11-182/275.8 m; and BTIC Dunite Inclusion from BT-11-199A/46.2 m.

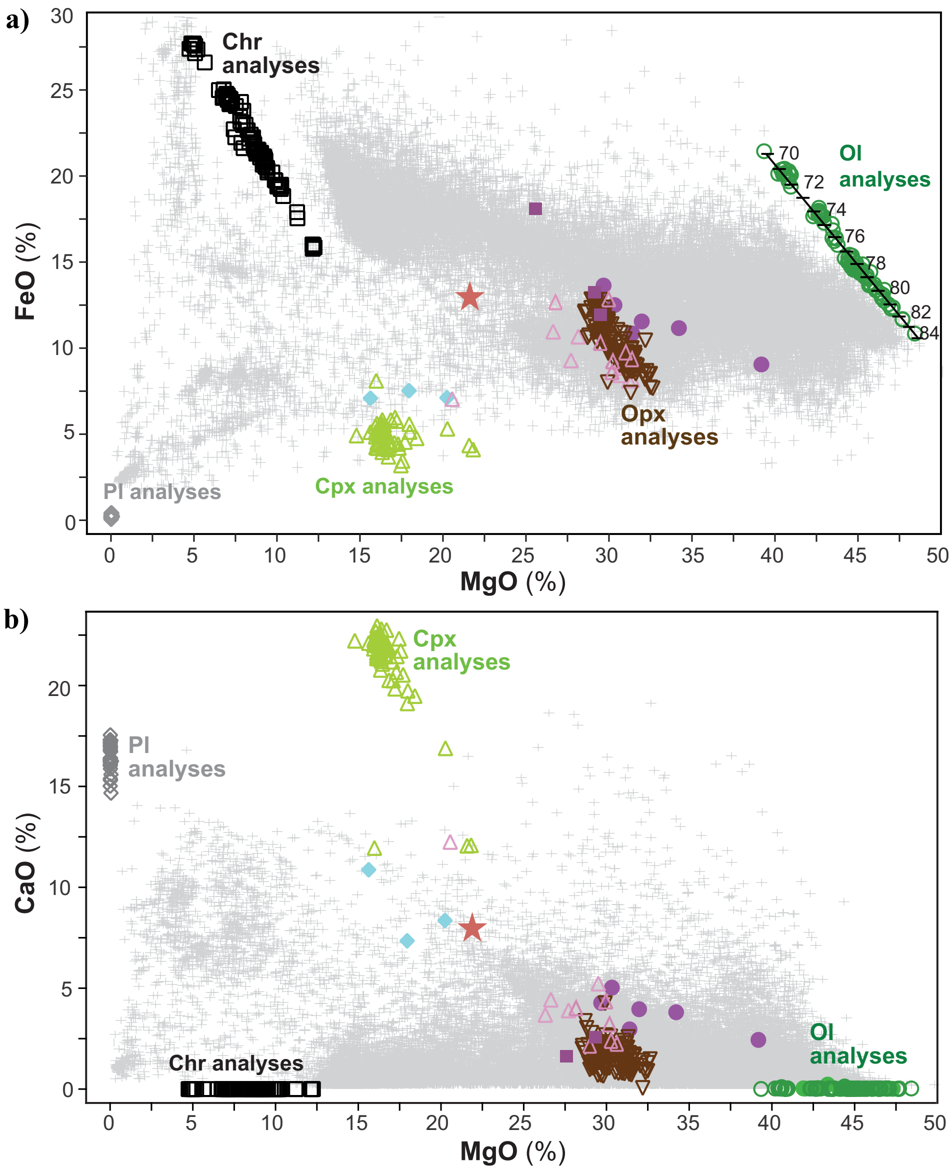

Figure 4. a) MgO versus FeO and **(b)** MgO versus CaO variation diagrams for BTIC, LWI, and hybrid lithologies. BLHZ chromitite harzburgite trends from LWI toward chromite; BLHZ harzburgite trends from LWI toward olivine. Mineral analyses are from WDS-XRES (EPMA) analysis (representative analyses shown in Table 2). Also shown are compositions from a suite of samples from Cliffs Natural Resources Database (pale grey crosses) and mineral compositions from this study. Abbreviations: BL = Black Label; BLHZ = Black Label hybrid zone; BTIC = Black Thor intrusive complex; Chr = chromite; Cpx = clinopyroxene; LWI = late websterite intrusion; Ol = olivine; Opx = orthopyroxene; Pl = plagioclase.

Orthopyroxene in the LWI (in both websterite and gabbro) ranges from En_{78} to En_{84} and clinopyroxene ranges from Wo_{47} En_{48} Fs_5 to Wo_{41} En_{52} Fs_7 in composition. Orthopyroxene in BTIC inclusions (dunite and net-textured chromitite lithologies) ranges from En_{83} to En_{87} and clinopyroxene ranges Wo_{47} En_{48} Fs_5 to Wo_{45} En_{51} Fs_4 in composition. Orthopyroxene in BLHZ (both hybrid lithologies) ranges from En_{82} to En_{85} and clinopyroxene ranges from Wo_{46} En_{49} Fs_5 to Wo_{40} En_{52} Fs_8 in composition. Plagioclase in the LWI gabbro is significantly more calcic compared to plagioclase in LWI websterite and ranges from An_{87} to An_{83} in gabbro and from An_{83} to An_{78} in websterite.

Whole-Rock Geochemistry

The majority of the rocks in the BTIC are olivine ± chromite ± orthopyroxene ± (clinopyroxene) adcumulate to mesocumulate rocks, that define three broad trends on MgO variation plots (Fig. 4; see also Carson et al., 2015):

1. A mixing trend between olivine-rich and chromite-rich cumulate rocks;
2. A mixing trend between olivine-rich and orthopyroxene-rich cumulate rocks;
3. A fractionation trend between pyroxenite and gabbro.

The compositions of BLHZ chromite harzburgites (purple circles in Fig. 4), trend from LWI toward chromite, and BLHZ harzburgites (purple squares in Fig. 4), trend from LWI toward olivine. Trace element geochemistry (Fig. 5) of the LWI websterite shows a relatively flat pattern with positive U and light rare earth element anomalies and negative Th, Nb-Ta, and Sr anomalies. The negative Nb-Ta anomalies suggest incorporation of an upper crustal component; the negative Sr anomalies probably reflects greater mobility

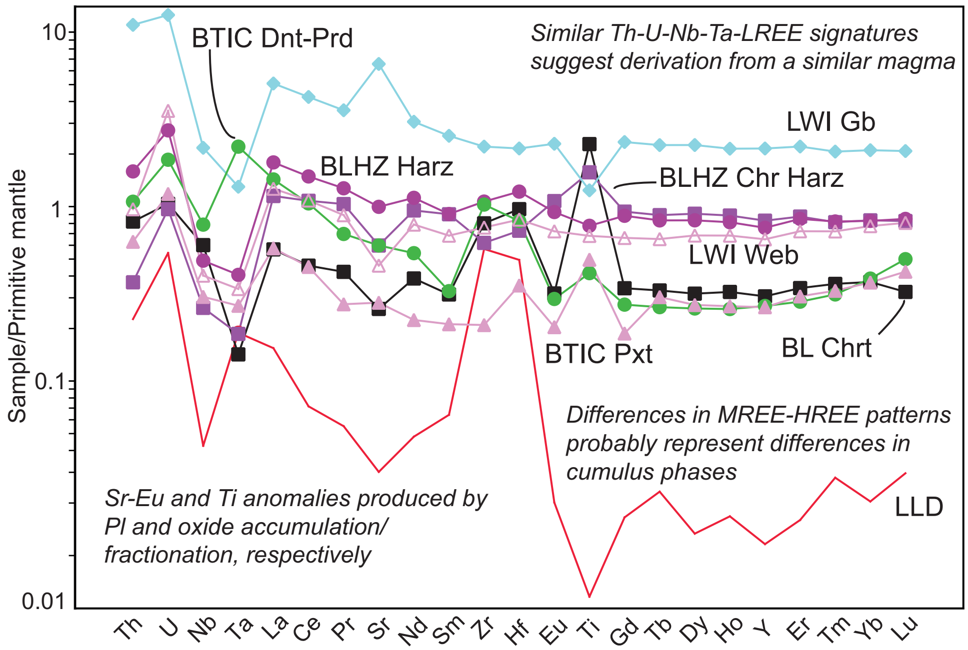

Figure 5. Trace element spider plot of representative samples of LWI, BTIC, and hybrid rock types. Signatures are labeled and symbols correspond to the legend in Figure 4. Normalizing values after McDonough and Sun (1995). Abbreviations: BL = Black Label; BLHZ = Black Label hybrid zone; BTIC = Black Thor intrusive complex; Chrt = chromitite; Dnt = dunite; Gb = gabbro; Harz = harzburgite; LLD = lower limit of detection; LWI = late websterite intrusion; Prd = peridotite; Pxt = pyroxenite; Web = websterite.

during alteration. The hybrid rocks posses Th-U-Nb-Ta-Ti-REE signatures similar to BTIC and LWI.

DISCUSSION

Hybridization Processes

Formation of the BLHZ appears to have involved three main processes: 1) mechanical disaggregation of BTIC rocks by LWI magma, 2) partial melting of BTIC inclusions by LWI magma, and 3) chemical re-equilibration of the remaining material of the BTIC inclusions with LWI magma.

Mechanical Disaggregation

The physical injection of LWI melt into the lower and middle ultramafic parts of the BTIC mechanically brecciated adjacent rocks, forming inclusions that were incorporated into LWI melt. Inclusions were disaggregated along their margins into smaller inclusions or individual xenocrysts of olivine and chromite (Figs. 2, 3). Mixing of the inclusions and xenocrysts with the LWI magma likely formed most of the hybrid lithologies. The semi-consolidated nature of the inclusions, forceful injections of the late melt, and other hybridization processes (e.g. partial melting of interstitial phases) may have facilitated this disaggregation.

Partial Melting

Partial melting of lower temperature phases in BTIC inclusions locally left only rounded olivine and euhedral chromite as xenocrysts, suggesting that the remainder of the original minerals in the BTIC inclusions (clinopyroxene ± orthopyroxene ± interstitial melt) were melted. This process would have weakened the olivine ± chromite cumulate framework and facilitated disaggregation. Experimental studies (see review in Arndt et al., 2008) indicate that lower temperature phases will disappear at temperatures above 1190°C at 1 atm, so the temperature of the LWI magma can be inferred to have been higher than 1190°C.

Chemical Re-equilibration

Chemical re-equilibration also appears to have occurred between the silica-rich hybrid melt and remaining olivine xenocrysts. This re-equilibration is supported by the presence of irregular, blebby geometries and corrosive margins of olivine chadacrysts and xenocrysts, indicating that they have reacted with LWI melt. This process is especially apparent in net-textured chromitite, where LWI melt invaded and chemically reacted with olivine to form a chromite-free orthopyroxene halo around a residual core of olivine (Fig. 3d). The inferred reaction is

$$(Mg,Fe)_2SiO_{4\ (Ol)} + SiO_{2\ (LWI\ melt)} \rightarrow 2(Mg,Fe)SiO_{3\ (Opx)}$$

Inclusion Variability

Megascopic and microscopic observations suggest that the sizes, shapes, sharpness of margins, and compositions of inclusions are controlled by the thickness, initial temperature, and the layered rock types present in the source rock (BTIC), as well as the degree of thermal equilibration between the wall rock and the intruding magma:

1. The LWI commonly intrudes bedding within the BTIC, so the thickness of the bedding and the nature of the original contacts (sharp versus irregular versus diffuse: Fig. 2) influences the rock types

(homolithic versus heterolithic), sizes, and shapes (subspherical versus tabular) of inclusions (Fig. 2).

2. Inclusions are subangular to subrounded at the basal contact, and rounded to amoeboidal in the core and at the top margin of LWI, indicating that the BTIC was incompletely crystallized with a hotter, semi-solid core and cooler peripheries adjacent to the granodiorite footwall. Hotter, less consolidated wall rocks are more likely to form inclusions with irregular shapes, whereas cooler, more consolidated wall rocks are more likely to form angular inclusions.
3. More refractory chromitite inclusions tend to have more angular geometries than less refractory dunite-lherzolite inclusions. However, all inclusion rock types exhibit a range of shapes, indicating that the initial temperature and degree of consolidation varied in the system. Where rounded to amoeboidal geometries are present, the precursor rock was hotter and less consolidated, and where subangular to subrounded geometries are present, the precursor rock was cooler and more consolidated.
4. Inclusions that were incorporated earlier in the process are more likely to have irregular shapes than inclusions incorporated later in the process, due to thermal equilibration (e.g. partial melting of lower temperature phases).

Petrogenesis

Trends of increasing Ni-Mg and decreasing Al-Ti in hybrid harzburgite reflect variable degrees of incorporation of olivine into LWI magma, whereas increasing Ni-Mg-Cr and decreasing Al-Ti in hybrid chromite harzburgite reflect variable degrees of incorporation of olivine and chromite into LWI magma. The similar Th-U-Nb-Ta-LREE signatures of LWI and BTIC suggest derivation from similar sources.

IMPLICATIONS FOR EXPLORATION

The intrusion of LWI magma does not appear to have consumed BLCZ, but it has diluted the grade of the chromite mineralization by dispersing it within the LWI magma. The Fe-Ni-Cu-(PGE) sulphide mineralization associated with LWI hybrid rocks is texturally, mineralogically, and geochemically slightly different from Fe-Ni-Cu-(PGE) sulphide mineralization along the basal contact of the BTIC. Both are clearly magmatic, but the mineralization associated with BLHZ breccia clearly formed during the magma interaction process. Further characterization of the hybrid rocks and inclusion-variability is in progress and will help to establish the range and variability of processes within the BTIC, and their influence on the genesis of associated Fe-Ni-Cu-(PGE) sulphide mineralization in the BLHZ.

ACKNOWLEDGEMENTS

This ongoing project is being supported by grants from Cliffs Natural Resources, the Natural Sciences and Engineering Research Council of Canada (NSERC) Collaborative Research and Development Program, the Ontario Geological Survey (OGS), the Society of Economic Geologists (SEG) Fellowship Program, the Ontario Graduate Scholarship Program, and the Targeted Geoscience Initiative 4 (TGI-4) of the Geological Survey of Canada (GSC). We are also grateful to R. Metsaranta (OGS) for comprehensive reviews that helped us improve the final version of this contribution.

REFERENCES

Arndt, N., Lesher, C.M., and Barnes, S.J., 2008. Komatiite; Cambridge, UK, University Press, 467 p.

Carson, H.J.E., Lesher, C.M., and Houlé, M.G., 2015. Geochemistry and petrogenesis of the Black Thor intrusive complex and associated chromite mineralization, McFaulds Lake greenstone belt, Ontario *In:* Targeted Geoscience Initiative 4: Canadian Nickel-Copper-Platinum Group Elements-Chromium Ore Systems — Fertility, Pathfinders, New and Revised Models, (ed.) D.E. Ames and M.G. Houlé; Geological Survey of Canada, Open File 7856, p. 87–102.

Farhangi, N., Lesher, C.M., and Houlé, M.G., 2013. Mineralogy, geochemistry and petrogenesis of nickel-copper-platinum group element mineralization in the Black Thor intrusive complex, McFaulds Lake greenstone belt, Ontario, *In:* Summary of Field Work and Other Activities, 2013; Ontario Geological Survey, Open File Report 6290, p. 55-1 to 55-7.

McDonough, W.F. and Sun, S.-S., 1995. Composition of the Earth; Chemical Geology, v. 120, p. 223–253. doi: 10.1016/0009-2541(94)00140-4

Mungall, J.E., Harvey, J.D., Balch, S.J., Azar, B., Atkinson, J., and Hamilton, M.A., 2010. Eagle's Nest: A magmatic Ni-sulfide deposit in the James Bay Lowlands, Ontario, Canada, *In:* The Challenge of Finding New Mineral Resources: Global Metallogeny, Innovative Exploration, and New Discoveries, Volume I: Gold, Silver, and Copper-Molybdenum, (ed.) R.J. Goldfarb, E.E. Marsh, and T. Monecke; Society of Economic Geologists, Special Publication 15, p. 539–559.

Weston, R. and Shinkle, D.A., 2013. Geology and stratigraphy of the Black Thor and Black Label chromite deposits, James Bay Lowlands, Ontario, Canada, *In:* Abstracts; Society for Geology Applied to Minerals, 12th SGA Biennial Meeting, Uppsala, Sweden, August 12–15, 2013, Proceedings, v. 3, p. 1069–1071.