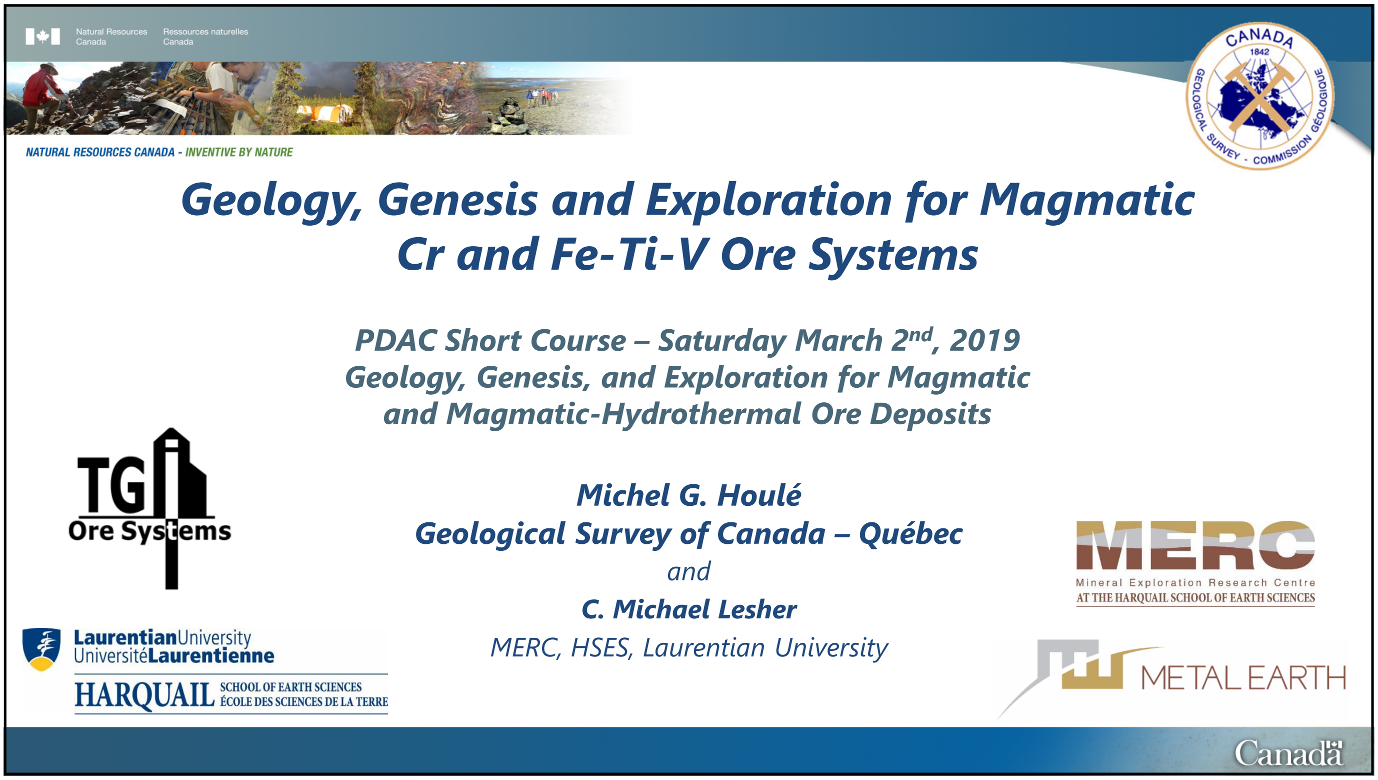
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CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE
Geology, Genesis and Exploration for Magmatic Cr and Fe-Ti-V Ore Systems
PDAC Short Course – Saturday March 2nd, 2019
Geology, Genesis, and Exploration for Magmatic and Magmatic-Hydrothermal Ore Deposits
Michel G. Houlé
Geological Survey of Canada – Québec
and
C. Michael Lesher
MERC, HSES, Laurentian University
TGI Ore Systems
MERC
Mineral Exploration Research Centre
AT THE HARQUAIL SCHOOL OF EARTH SCIENCES
LaurentianUniversity
UniversitéLaurentienne
HARQUAIL SCHOOL OF EARTH SCIENCES
ÉCOLE DES SCIENCES DE LA TERRE
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Geology, Genesis and Exploration for Magmatic Chrome Ore Systems
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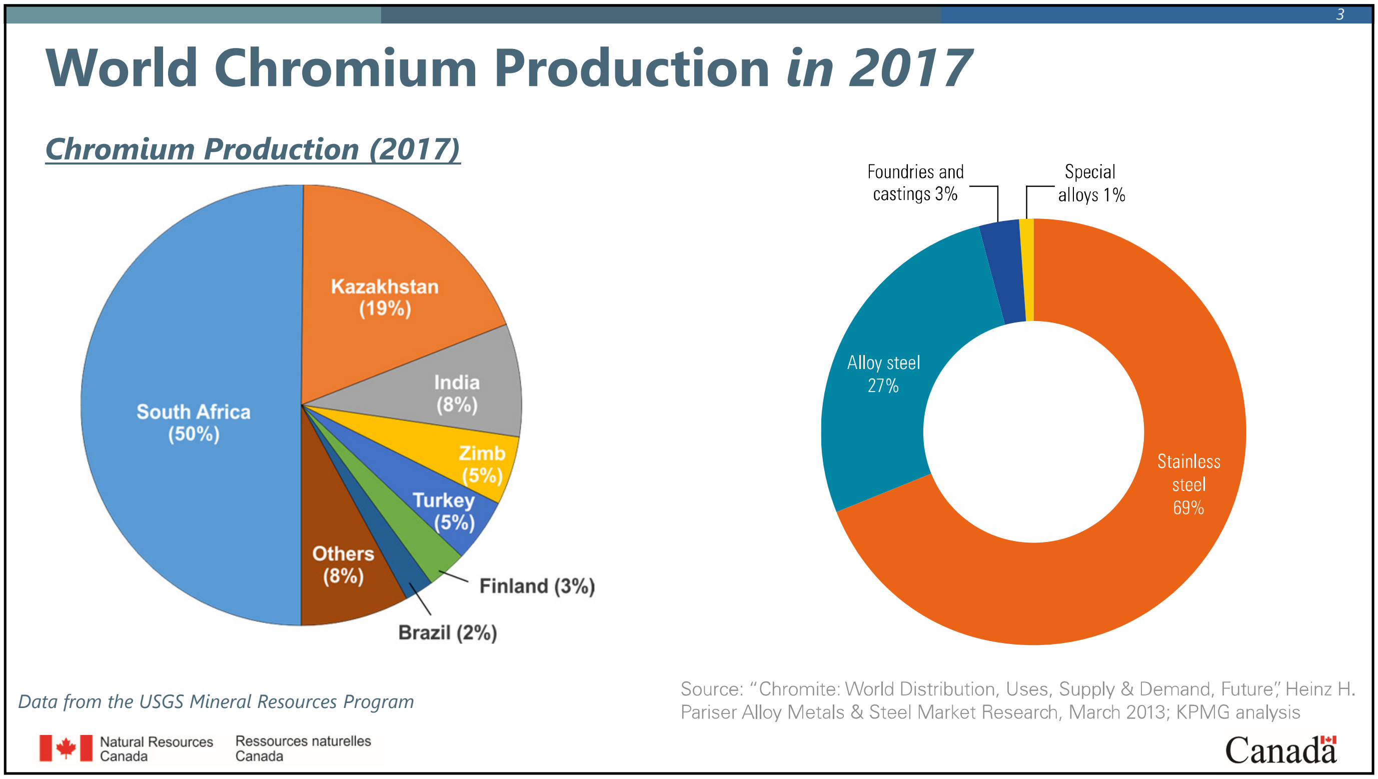
3
World Chromium Production in 2017
Chromium Production (2017)
South Africa (50%)
Kazakhstan (19%)
India (8%)
Zimb (5%)
Turkey (5%)
Finland (3%)
Brazil (2%)
Others (8%)
Foundries and castings 3%
Special alloys 1%
Alloy steel 27%
Stainless steel 69%
Data from the USGS Mineral Resources Program
Source: "Chromite: World Distribution, Uses, Supply & Demand, Future", Heinz H. Pariser Alloy Metals & Steel Market Research, March 2013; KPMG analysis
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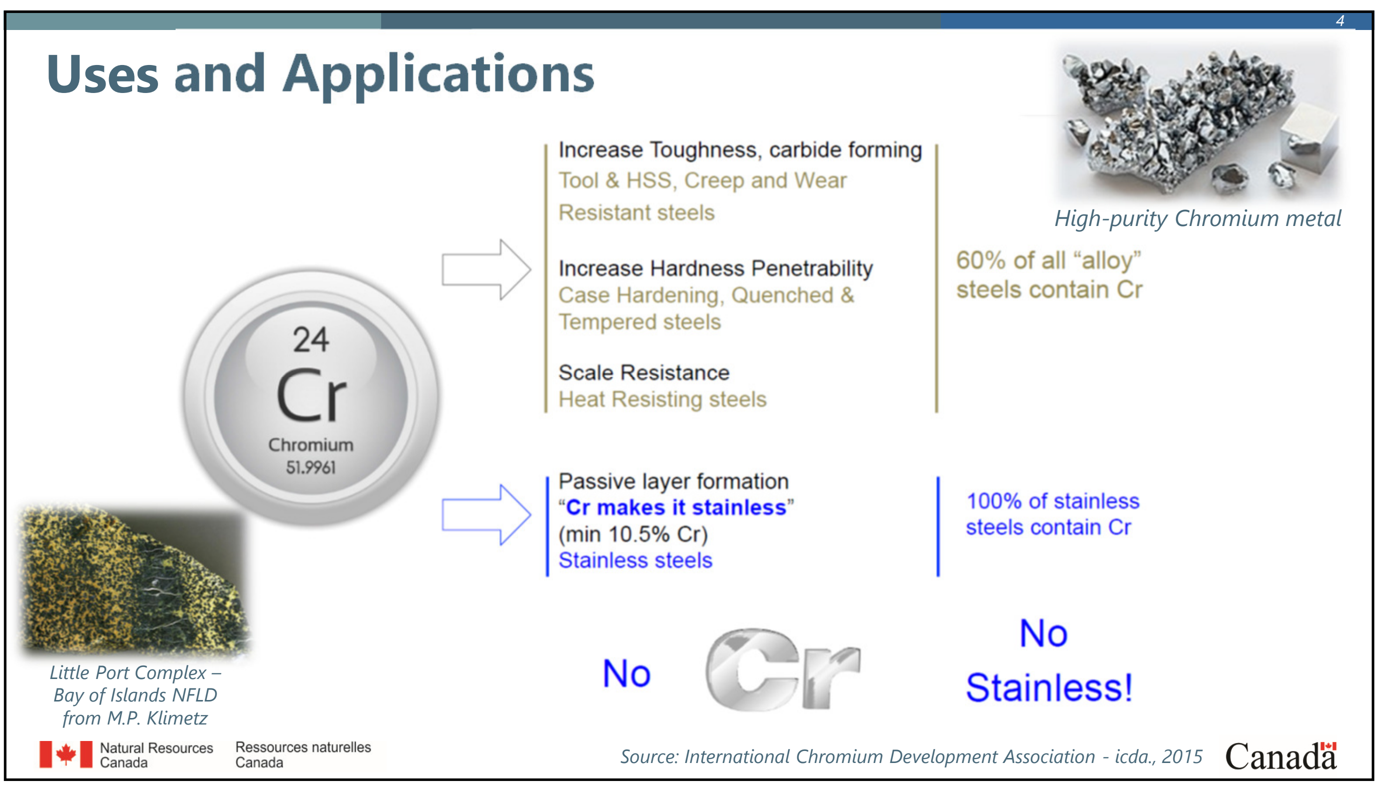
4
Uses and Applications
High-purity Chromium metal
24
Cr
Chromium
51.9961
Increase Toughness, carbide forming
Tool & HSS, Creep and Wear Resistant steels
Increase Hardness Penetrability
Case Hardening, Quenched & Tempered steels
Scale Resistance
Heat Resisting steels
60% of all "alloy" steels contain Cr
Passive layer formation
"Cr makes it stainless"
(min 10.5% Cr)
Stainless steels
100% of stainless steels contain Cr
No
Cr
No Stainless!
Little Port Complex – Bay of Islands NFLD from M.P. Klimetz
Source: International Chromium Development Association - icda., 2015
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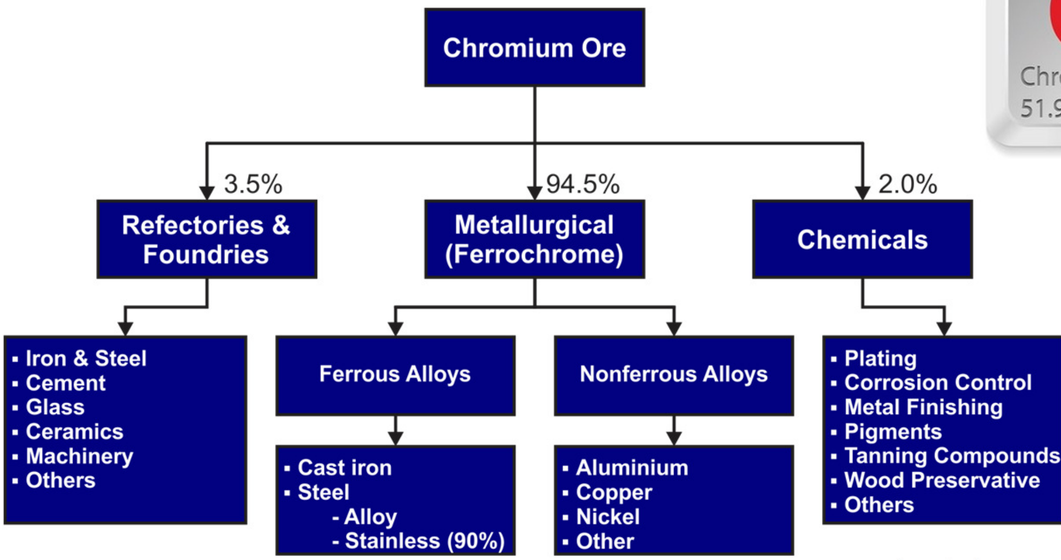
5

Uses and Applications



Source: Ideas 1st Information Services Pvt. Ltd., 2010

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6

Chromite Grades & Specifications

	Refractory 1%	Chemical 2%	Metallurgical 94%	Foundry 3%
Use	cement kiln fiberglass furnace	plating corrosion control metal finishing pigments tanning chemicals	cast iron steel alloys stainless steel Al-Cu-Ni alloys	foundry sands
Cr_2O_3	33-38%	42-46%	46-55%	>46%
Cr/Fe	-	<2	>2	-
Al_2O_3	22-34%	-	-	-
Fe	<10%	>21-23%	<23-27.5%	-
SiO_2	<5%	<8%	2-12%	<1%

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7

Classification Scheme for Chromite Deposits

Chromite deposits have been traditionally been subdivided into STRATIFORM (I) and PODIFORM (II) types

(Stowe, 1987, 1994)

Numerous differences between these Chromite Deposits…

- ❖ Worldwide distribution
- ❖ Geological setting / host rocks
- ❖ Size and extension of the deposits
- ❖ Textural facies
- ❖ Chromite composition
- ❖ PGE content

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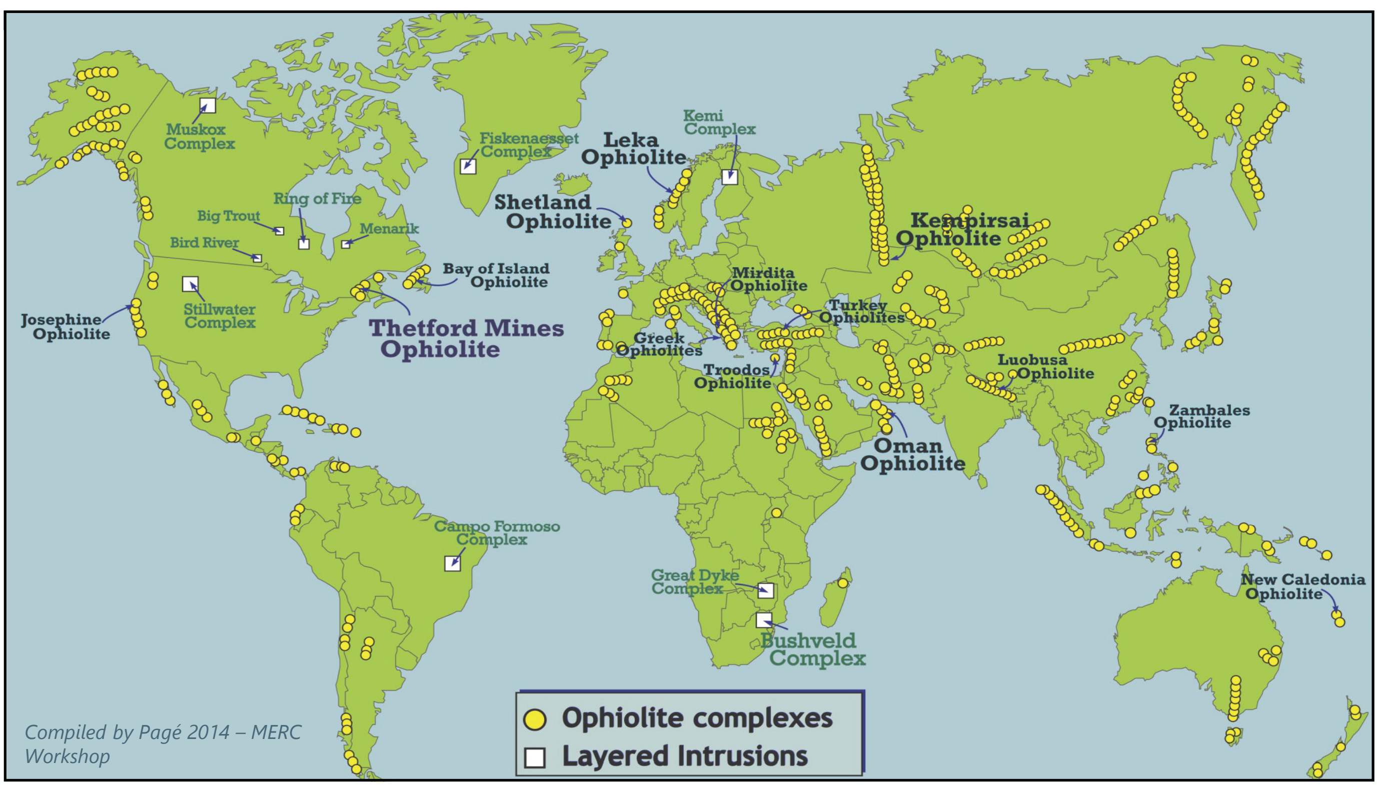
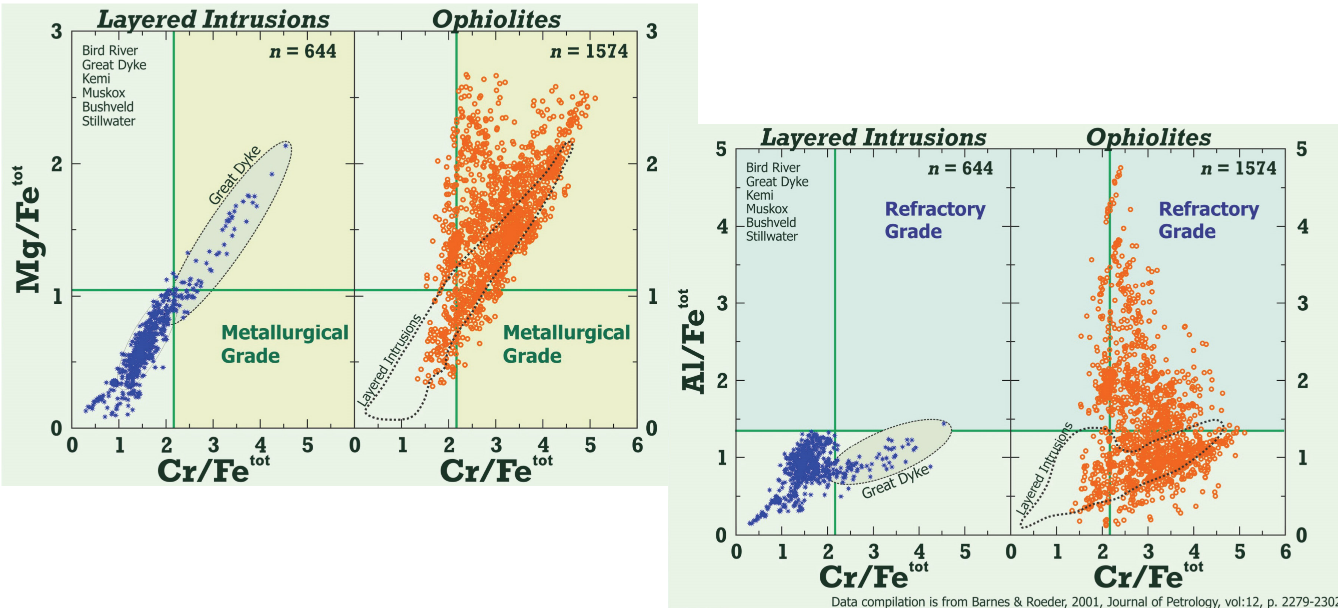


9

Classification Scheme for Chromite Deposits



From Pagé 2014 – MERC Workshop

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10

Classification Scheme for Chromite Deposits

Archean komatiitic-sill-hosted / Inyala-Railway Block-Prince *(Prendergast, 2008)*

- ❖ Although ***relatively unimportant in global resources potential***
- ❖ They have contributed significantly to the world supplies of chromite ore
- ❖ Merit a geologic recognition as a third principal deposit type

However, it has become clear, with recent studies…

- ❖ *Ring of Fire – Ontario*
- ❖ *Kemi – Finland*
- ❖ *Uitkomst – South Africa*
- ❖ *Sukinda-Nuasahi – India*
- ❖ *Ipueira-Medrado - Brazil*

…that type I deposits can be further subdivided into those hosted by large, differentiated layered intrusions (IA), and small, less-differentiated magmatic conduit (IB) *(Lesher et al., 2019 – Geology)*

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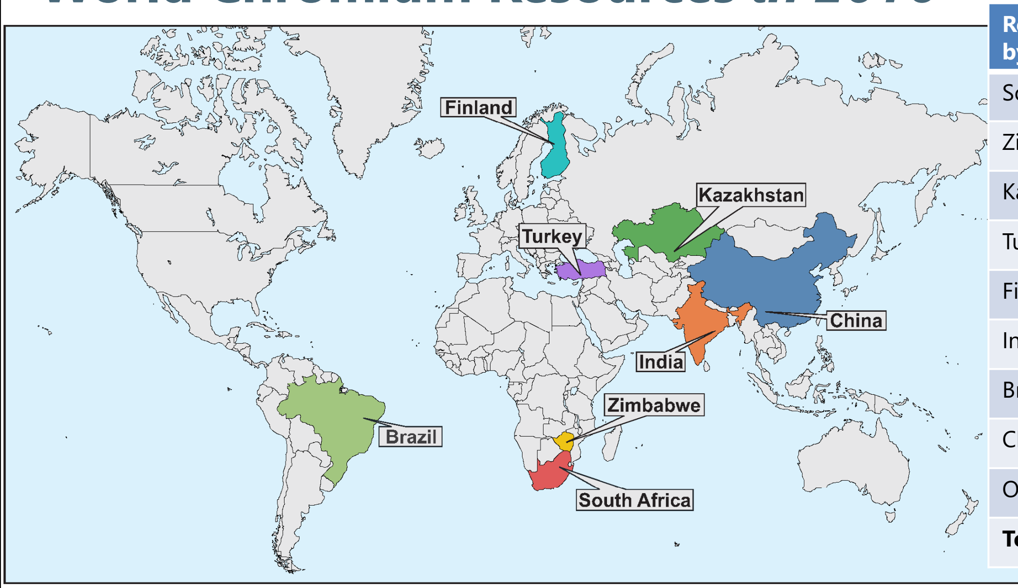
11

World Chromium Resources *in 2016*



Reserve base by Country	Mt	%
South Africa	6,751	74.1
Zimbabwe	930	10.2
Kazakhstan	387	4.2
Turkey	220	2.4
Finland	120	1.3
India	54	0.6
Brazil	18	0.2
China	5	0.1
Others	621	6.8
Total	**9,106**	**100**

Data from Outokumpu - 2016

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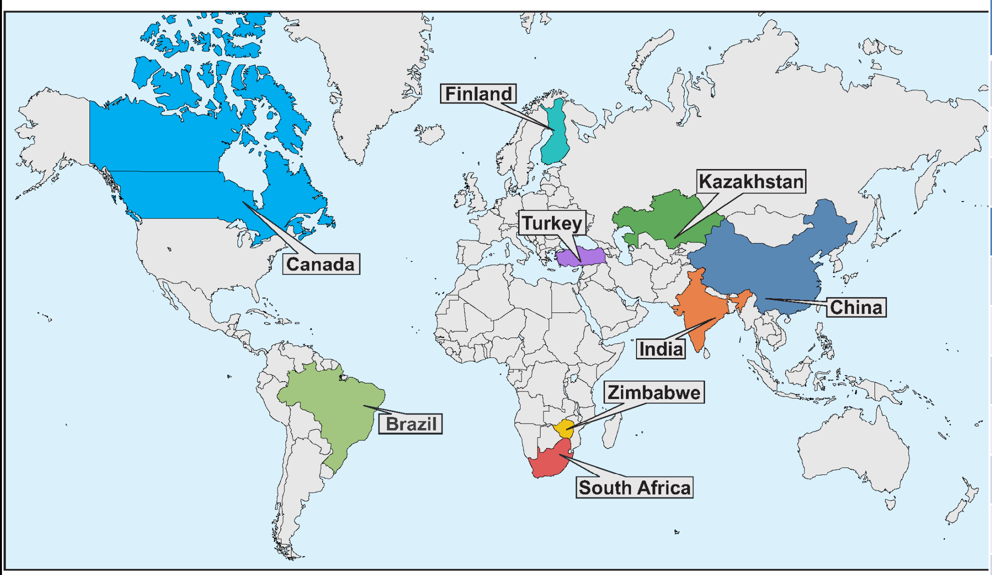
12

World Chromium Resources *in 2016*



Reserve base by Country	Mt	%
South Africa	6,751	74.1
Zimbabwe	930	10.2
Kazakhstan	387	4.2
Canada	**343**	**3.8**
Turkey	220	2.4
Finland	120	1.3
India	54	0.6
Brazil	18	0.2
China	5	0.1
Others	278	3.0
Total	**9,106**	**100**

Data from Outokumpu & others - 2016

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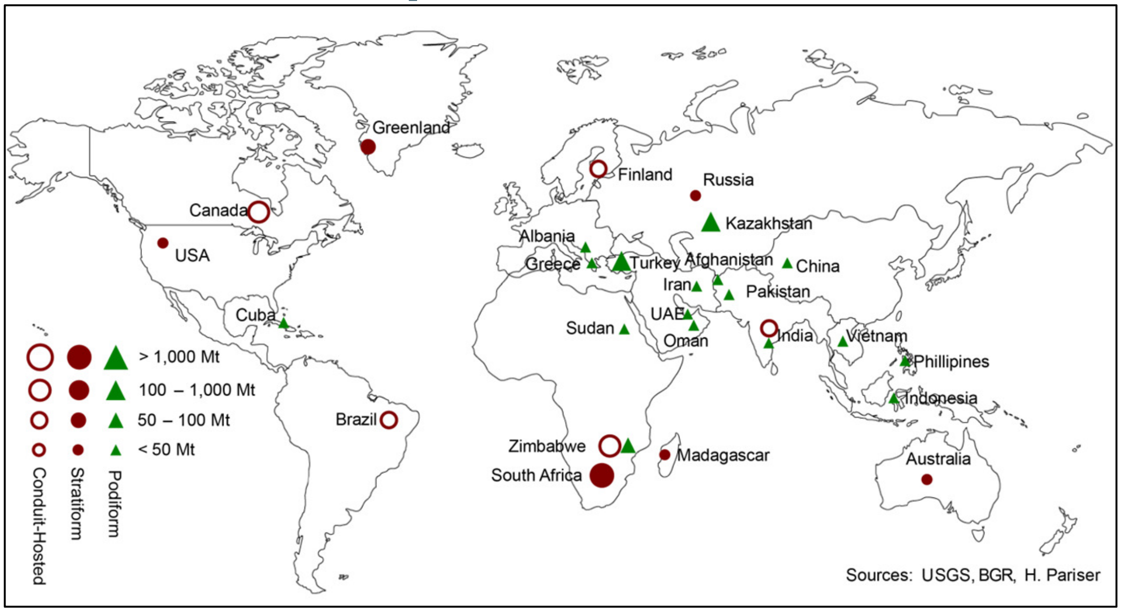
World Chromite Deposits



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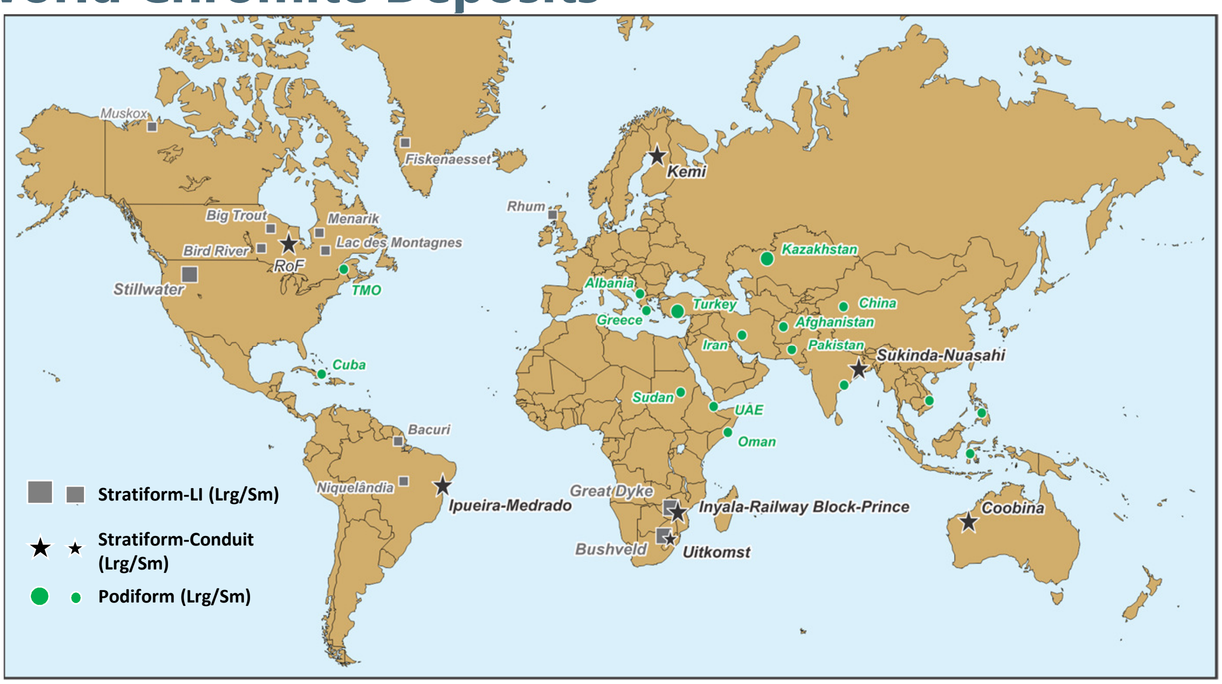
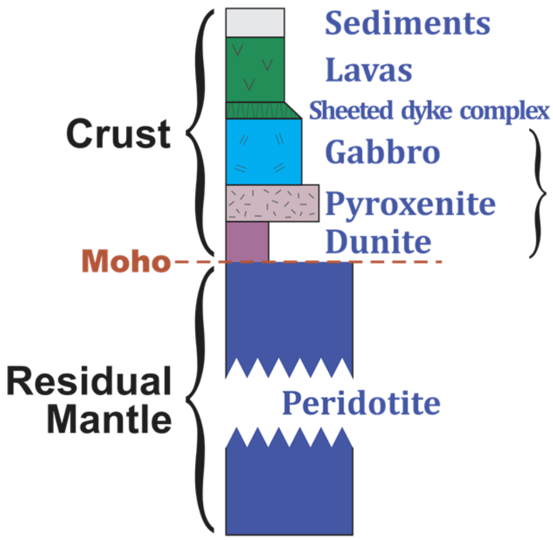
World Chromite Deposits



15

Podiform Chromite Deposit - Ophiolites



Slice of oceanic lithosphere...

- ***Subduction-unrelated***
  - Continental marging type
  - Mid-oceanic ridge type
  - Plume-type
- **Subduction-related**
  - Suprasubduction zone type
  - Volcanic arc type
- **Two types of mantle peridotites are recognized within these environments**
  - Harzburgite Ophiolite type (HOT)
  - Lherzolite Ophiolite type (LOT)

From Pagé 2014 – MERC Workshop

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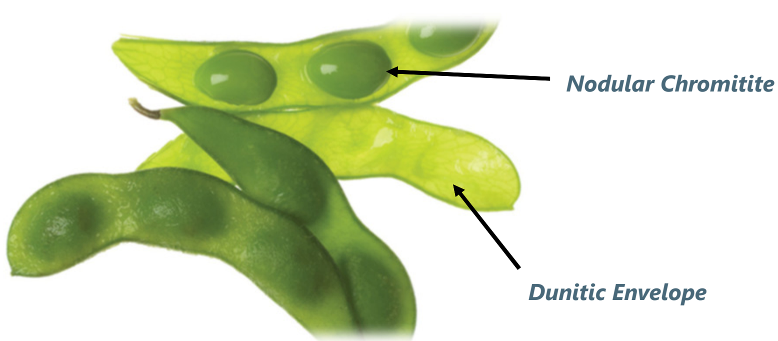
Podiform Chromite Deposits



This term has been used to refer t a deposit-type where chromitite deposits are associated with Ophiolitic Complexes

- *The term podiform has priority and inherently contrasts their lenticular nature with the great lateral persistence of the stratiform-type*

(Thayer, 1964)

Because of its shape, it is also referred as "Grape Ore"

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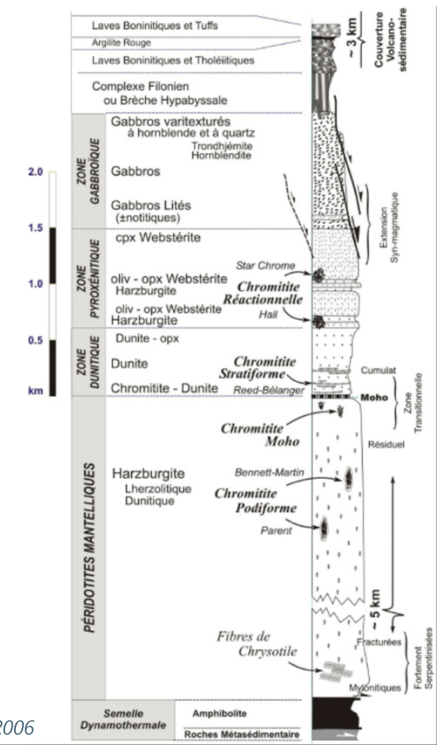
Podiform Chromite Deposits

Numerous classification scheme has been proposed:

- Pseudo-stratigraphy: mantle, transitional, crustal
- Structural: discordant, concordant, and subconcordant chromitites
- Chromite chemistry: high Cr# *(Cr# > 0.6)* & high Al *(Cr# < 0.6)*
- *Etc.*

Here, we used Pagé (2006) nomenclature

- *Podiform chromitite*
- *Stratiform chromitite, and*
- *Upper crust discordant (reactional chromitite)*



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From Pagé, 2006

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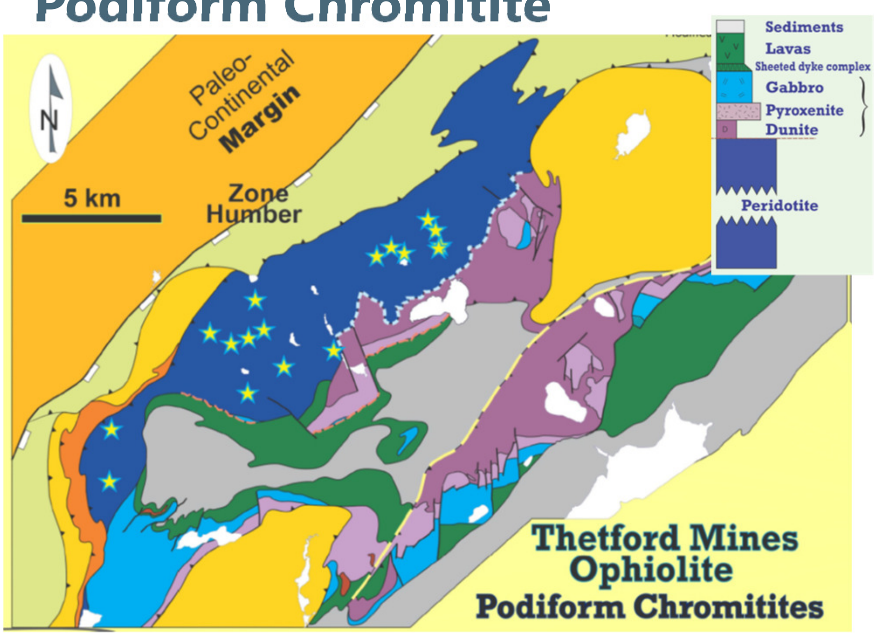
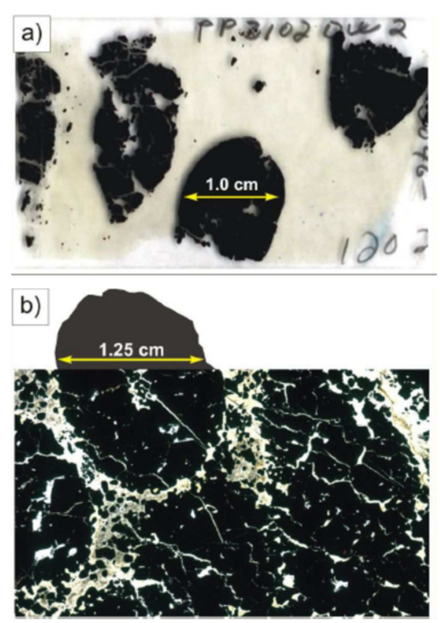
Podiform Chromitite





From Pagé 2006 & Pagé 2014 – MERC Workshop

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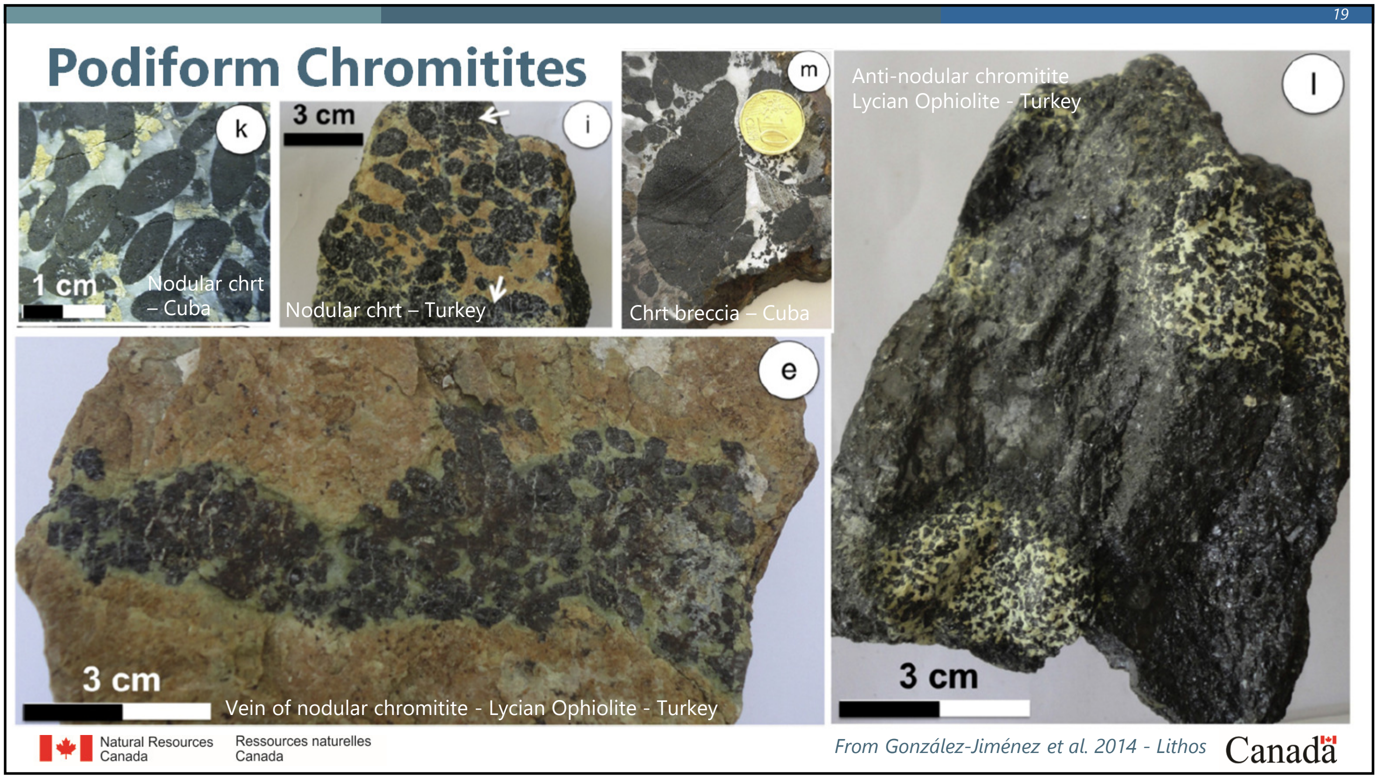
19
Podiform Chromitites
k
1 cm
Nodular chrt – Cuba
3 cm
i
Nodular chrt – Turkey
m
Chrt breccia – Cuba
Anti-nodular chromitite
Lycian Ophiolite - Turkey
l
e
3 cm
Vein of nodular chromitite - Lycian Ophiolite - Turkey
3 cm
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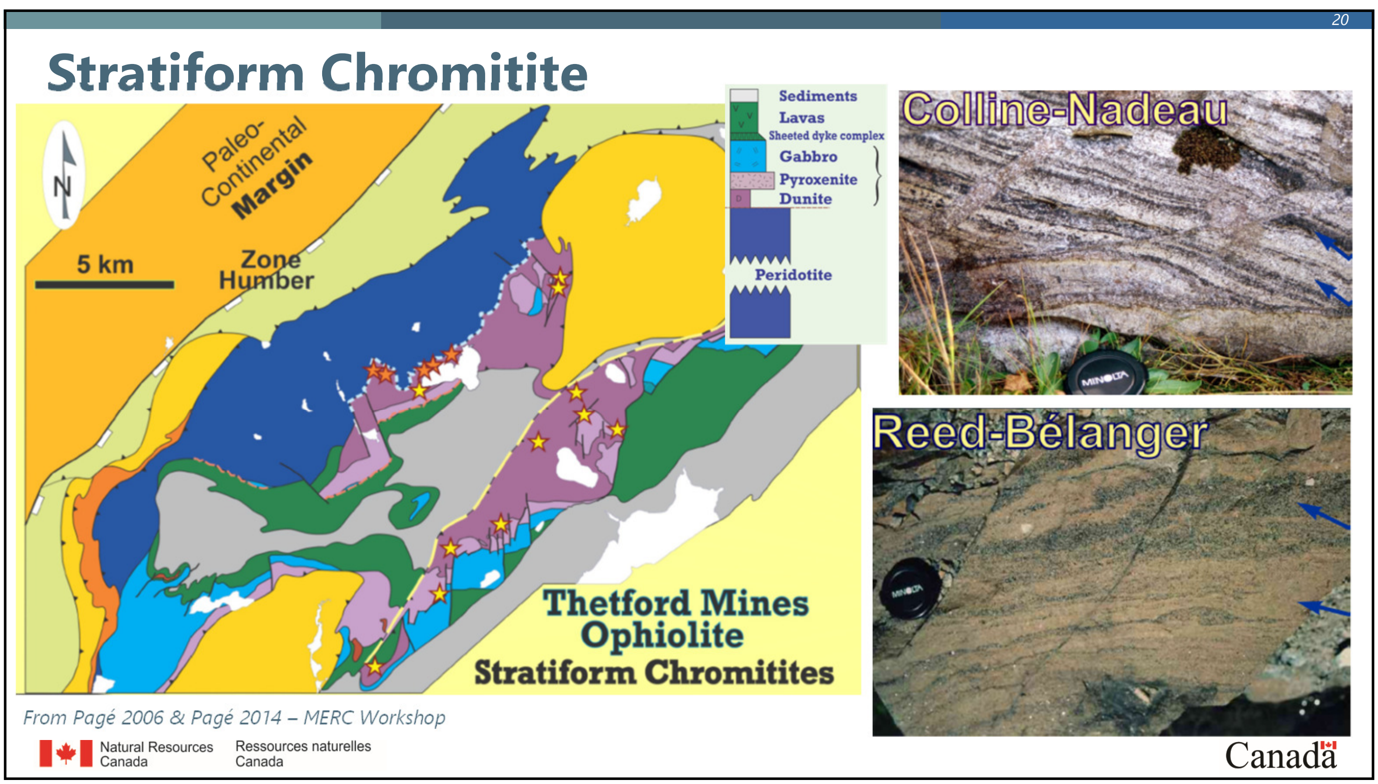
From González-Jiménez et al. 2014 - Lithos
Canada


20
Stratiform Chromitite
N
Paleo-Continental Margin
5 km
Zone Humber
Sediments
Lavas
Sheeted dyke complex
Gabbro
Pyroxenite
Dunite
Peridotite
Colline-Nadeau
Reed-Bélanger
Thetford Mines Ophiolite
Stratiform Chromitites
From Pagé 2006 & Pagé 2014 – MERC Workshop
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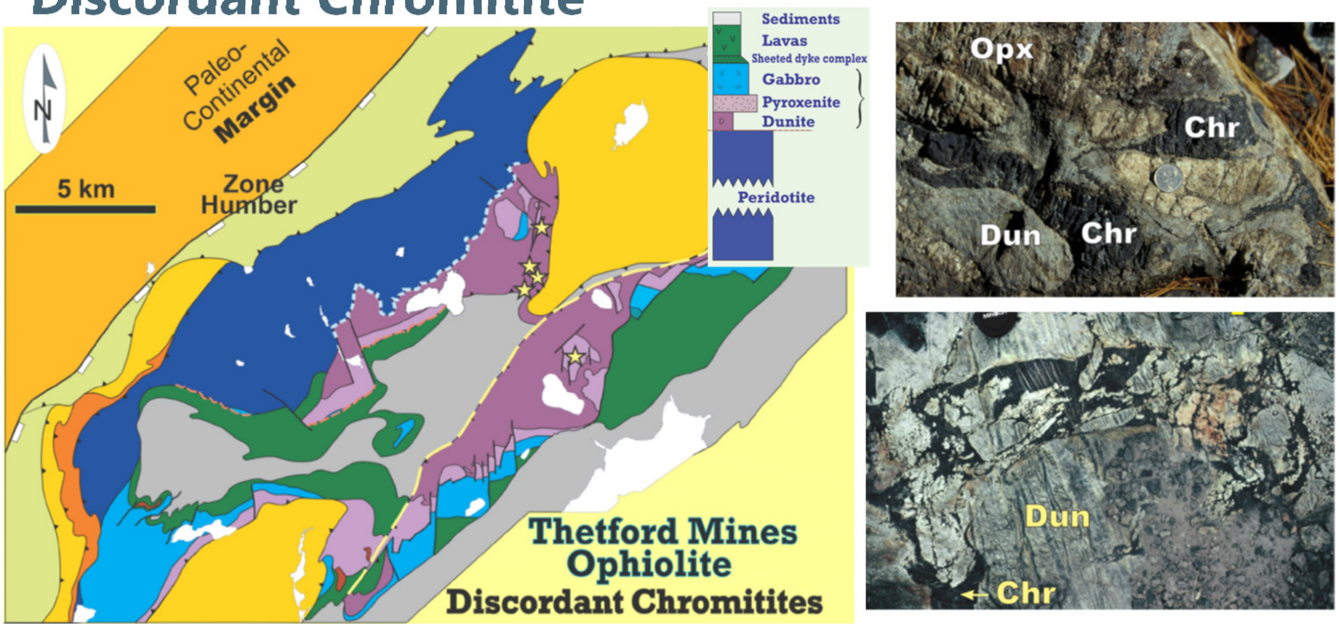
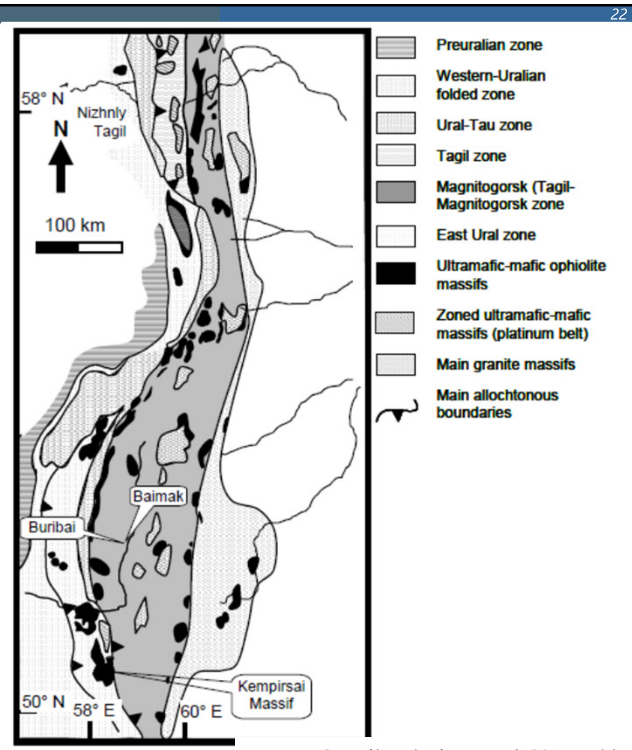
Discordant Chromitite



From Pagé 2006 & Pagé 2014 – MERC Workshop

Ophiolitic Deposits

- *Largest chromitite bodies are hosted by moderately refractory harzburgites containing spinels with Cr# between 0.4 and 0.6 (~HOT)*
- Fertile lherzolites (Cr# < 0.3) or highly refractory harzburgites (Cr# > 0.7) contain rare, and usually small, chromitites (~LOT)
- Most favorable setting is in suprasubduction zone (SSZ) with high extension rate
- Chromite deposits of this type are generally small *(50m x 5m)* but giant ore bodies can occurred
  - Kempirsai Massif, Kazakhstan (1500 × 200 m)
  - Masinloc in the Coto ophiolites, Philippines (600×300×80m)
  - Mercedita in the Moa-Baracoa district of eastern Cuba (600×250×20m)



From González-Jiménez et al. 2014 - Lithos

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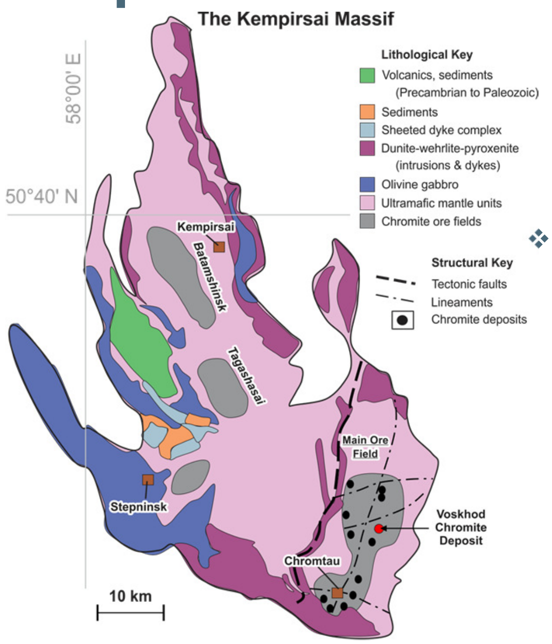
Kempirsai Massif



- The Batamshinsk, Tagashasai, Stepninsk Ore Fields reffered globally as the Batamshinsk -type (BAT) Chromite Ores *(High Al chromite)*
  - Pod and lens shaped orebodies(<100m x 10m), hosted in series of dnt-harz mantle units underlain by tectonised harz
  - At Stepninsk, orebodies are tens of m in length, <3m thick
- The Main Ore Field (MOF) *(High Cr, Al-poor chromite)*
  - ~50 deposits and associated ore showings located w/in MOF
  - Collectively, form the largest occurrence of podiform chromitite in the world (in terms of the number as well as unusually large size of the individual ore bodies)
  - Range of elongated morphologies occurring either as a single lens or as a series of discrete lenses serparated by weakly mineralised dunite horizons
  - Orebodies range in size from tens of meters to 1,800 m having thicknesses ranging from a few meters to 230 m

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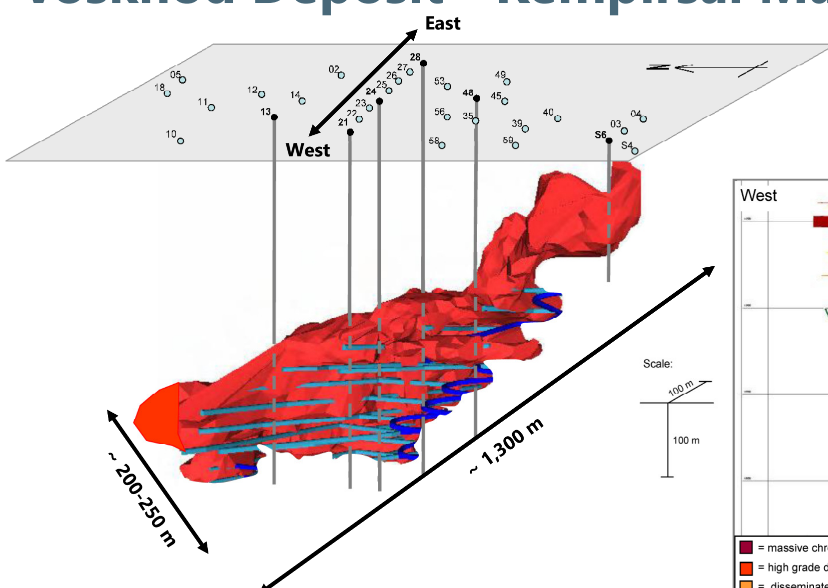
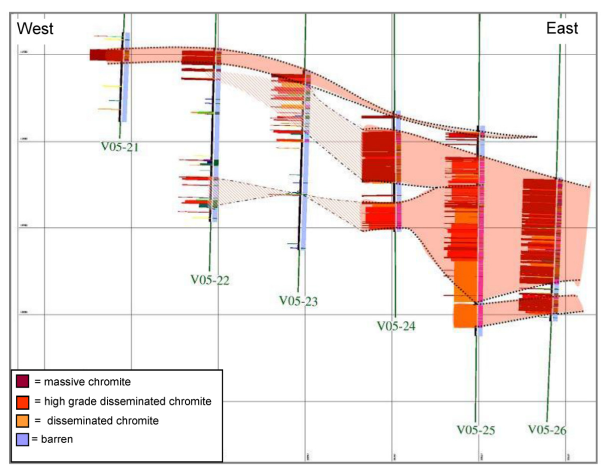
Voskhod Deposit - Kempirsai Massif





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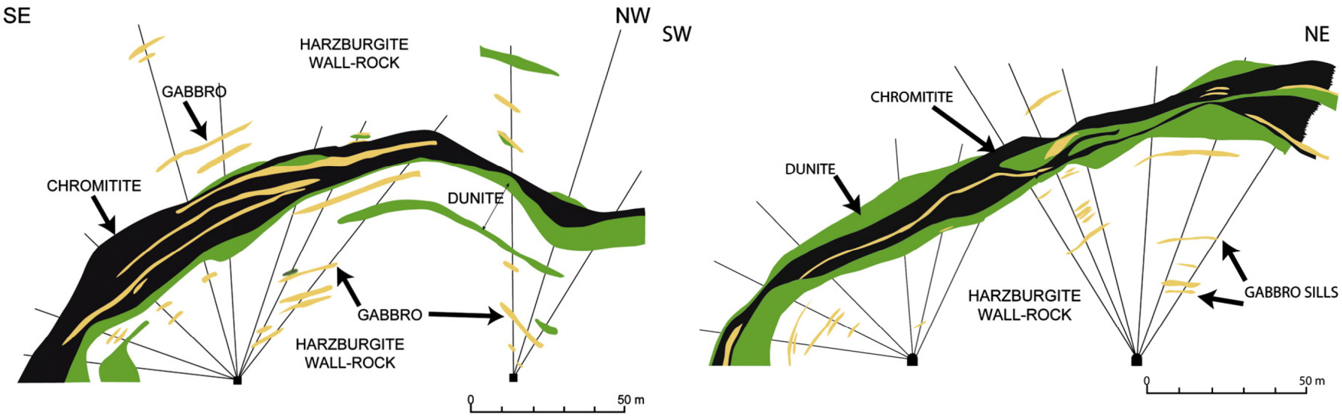
Mercedita Deposit – Mayari-Baracoa Ophiolite Cuba



From González-Jiménez et al. 2014 - Lithos

26

Stratiform Chromite Deposit (Type IA-IB)

Chromite deposits are typically divided into two main types: Stratiform and Podiform. Stratiform deposits can be further subdivided into:

- ***Large post-Archean layered intrusion-hosted deposits that represent periodically-replenished magma chambers*** (e.g., Bushveld Complex, South Africa; Stillwater Complex, USA) ***formed from silicious high-Mg basaltic magmas***

- ***Small-intermediate-sized Archean conduit-hosted deposits that represent flow-through magma systems*** (e.g., Kemi, Finland; Inyala and Railway Block, Zimbabwe; Ipueira-Medrado, Brazil; Sukinda, India; Nkomati, South Africa; Black Thor-Blackbird, Canada) ***formed from low-Mg komatiitic magmas***

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Stratiform Chromite Deposit (Type IA-IB)

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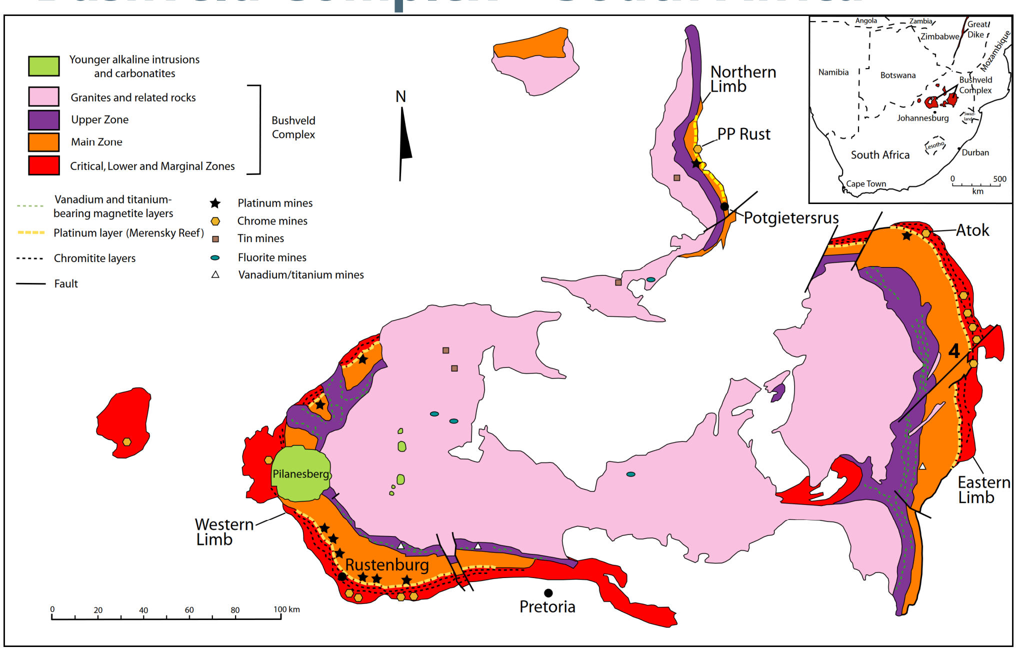
Bushveld Complex – South Africa



World Mineral Treasure:

Bushveld Igneous Complex

- World's largest layered mafic-ultramafic complex
  - Covering 66,000 km^2
- World largest chromite and PGEs resources
  - Chromite is confined within the Critical Zone
  - PGE is confined at the top of the Critical Zone near the Main Zone
- V mineralization occur throughout the Upper Zone
- Continuous over 100s km

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Taylor et al. 2009 – USGS

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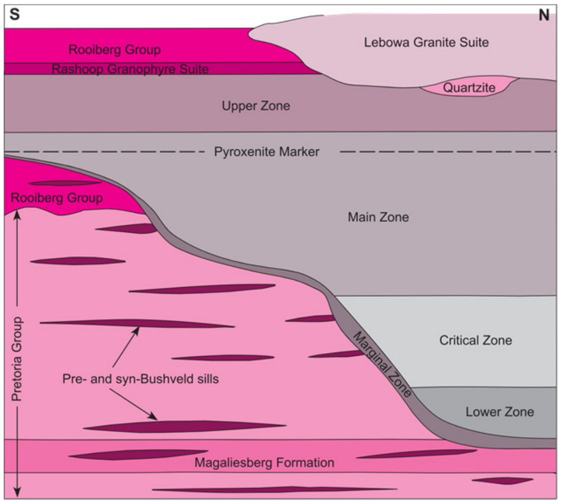
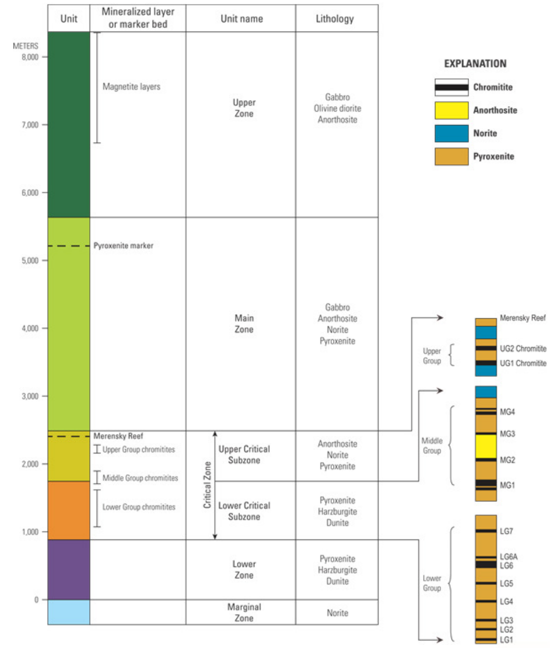
Bushveld Complex – South Africa



Harmer and Sharpe 19855



Schematic cross-section showing the upward expansion of the Bushveld magma chamber

Zientek et al. 2014 & Cawthorn 2015

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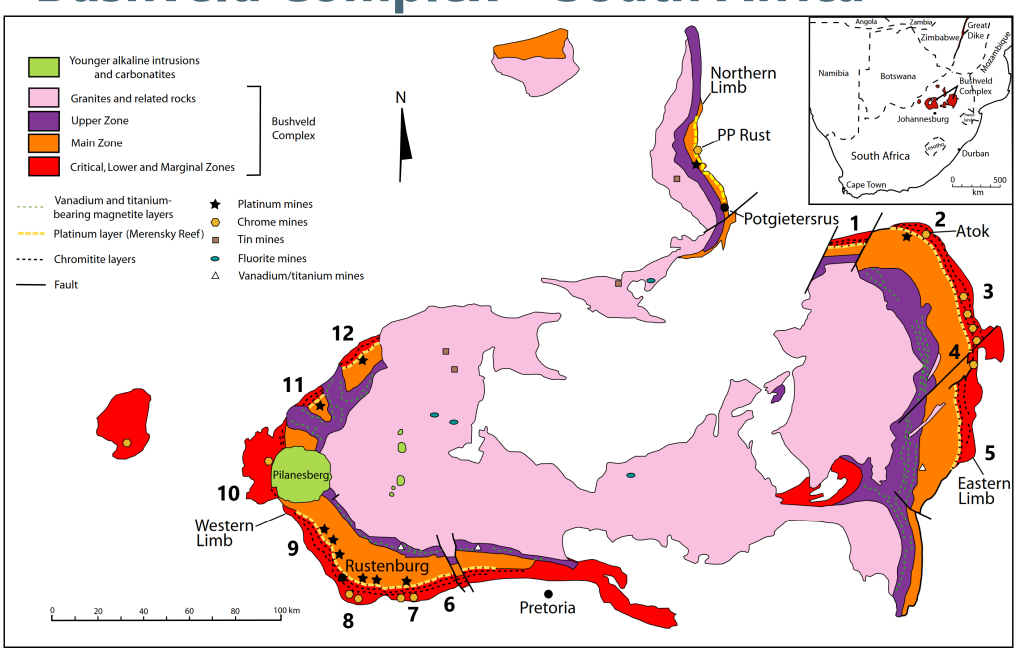
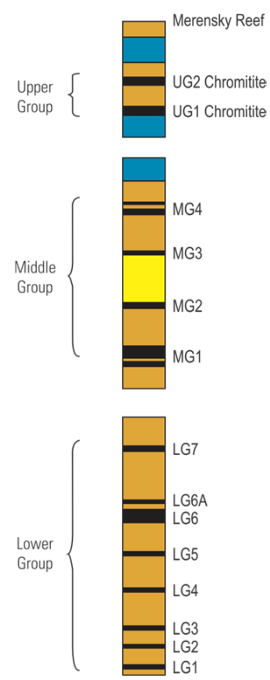
Bushveld Complex – South Africa





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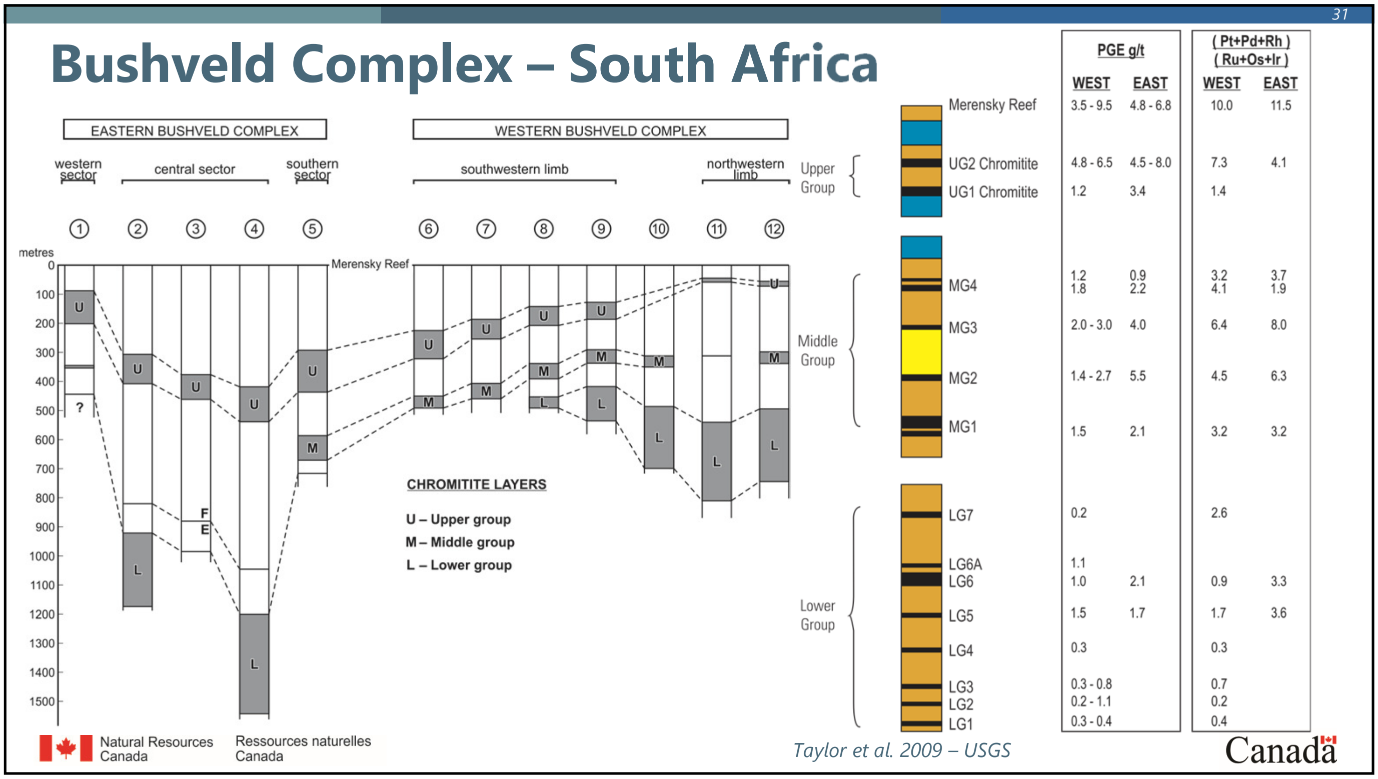
31
Bushveld Complex – South Africa
EASTERN BUSHVELD COMPLEX
WESTERN BUSHVELD COMPLEX
western sector
central sector
southern sector
southwestern limb
northwestern limb
metres
Merensky Reef
CHROMITITE LAYERS
U – Upper group
M – Middle group
L – Lower group
Upper Group
Middle Group
Lower Group
Merensky Reef
UG2 Chromitite
UG1 Chromitite
MG4
MG3
MG2
MG1
LG7
LG6A
LG6
LG5
LG4
LG3
LG2
LG1
PGE g/t
WEST EAST
(Pt+Pd+Rh) / (Ru+Os+Ir)
WEST EAST
Merensky Reef 3.5 - 9.5 4.8 - 6.8 10.0 11.5
UG2 Chromitite 4.8 - 6.5 4.5 - 8.0 7.3 4.1
UG1 Chromitite 1.2 3.4 1.4
MG4 1.2 1.8 0.9 2.2 3.2 4.1 3.7 1.9
MG3 2.0 - 3.0 4.0 6.4 8.0
MG2 1.4 - 2.7 5.5 4.5 6.3
MG1 1.5 2.1 3.2 3.2
LG7 0.2 2.6
LG6A 1.1
LG6 1.0 2.1 0.9 3.3
LG5 1.5 1.7 1.7 3.6
LG4 0.3 0.3
LG3 0.3 - 0.8 0.7
LG2 0.2 - 1.1 0.2
LG1 0.3 - 0.4 0.4
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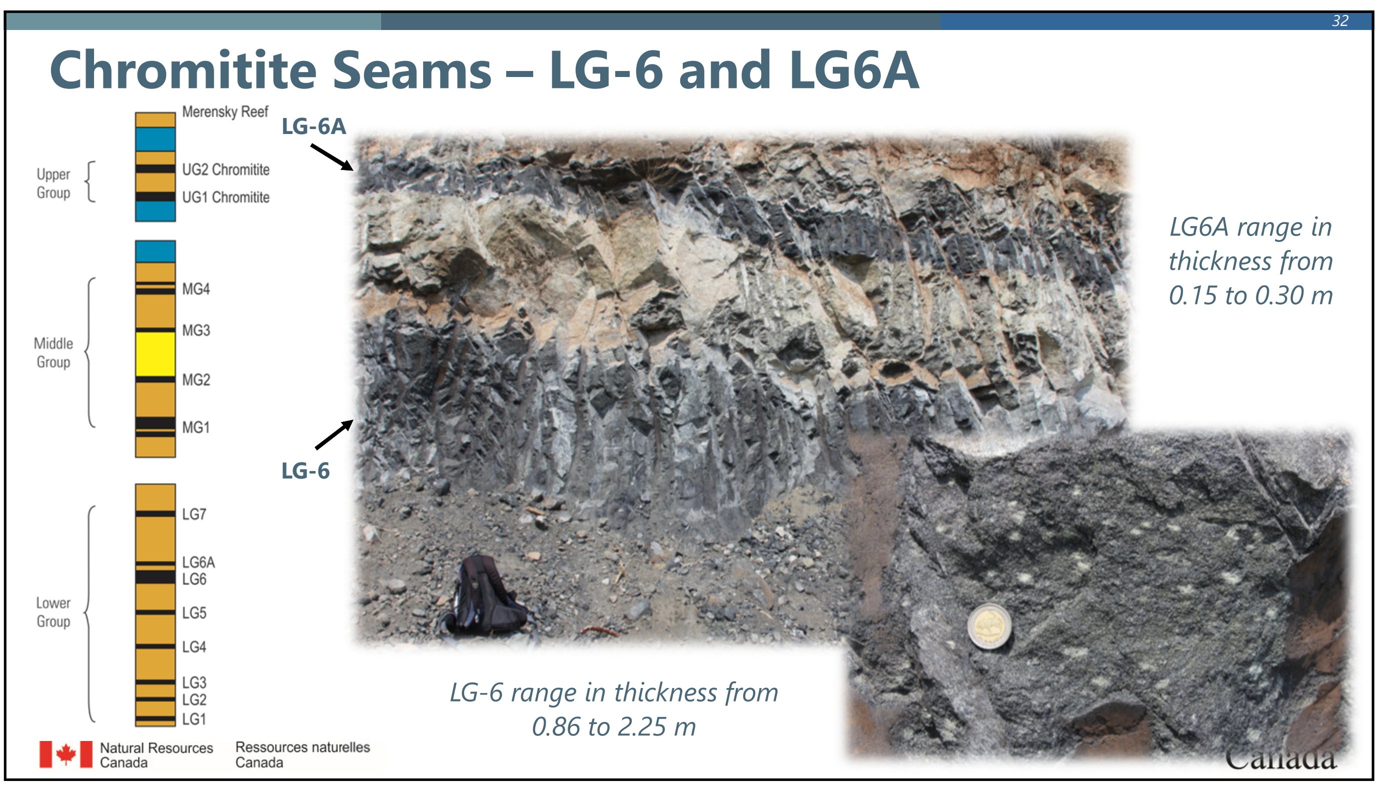
32
Chromitite Seams – LG-6 and LG6A
Merensky Reef
Upper Group
UG2 Chromitite
UG1 Chromitite
Middle Group
MG4
MG3
MG2
MG1
Lower Group
LG7
LG6A
LG6
LG5
LG4
LG3
LG2
LG1
LG-6A
LG-6
LG6A range in thickness from 0.15 to 0.30 m
LG-6 range in thickness from 0.86 to 2.25 m
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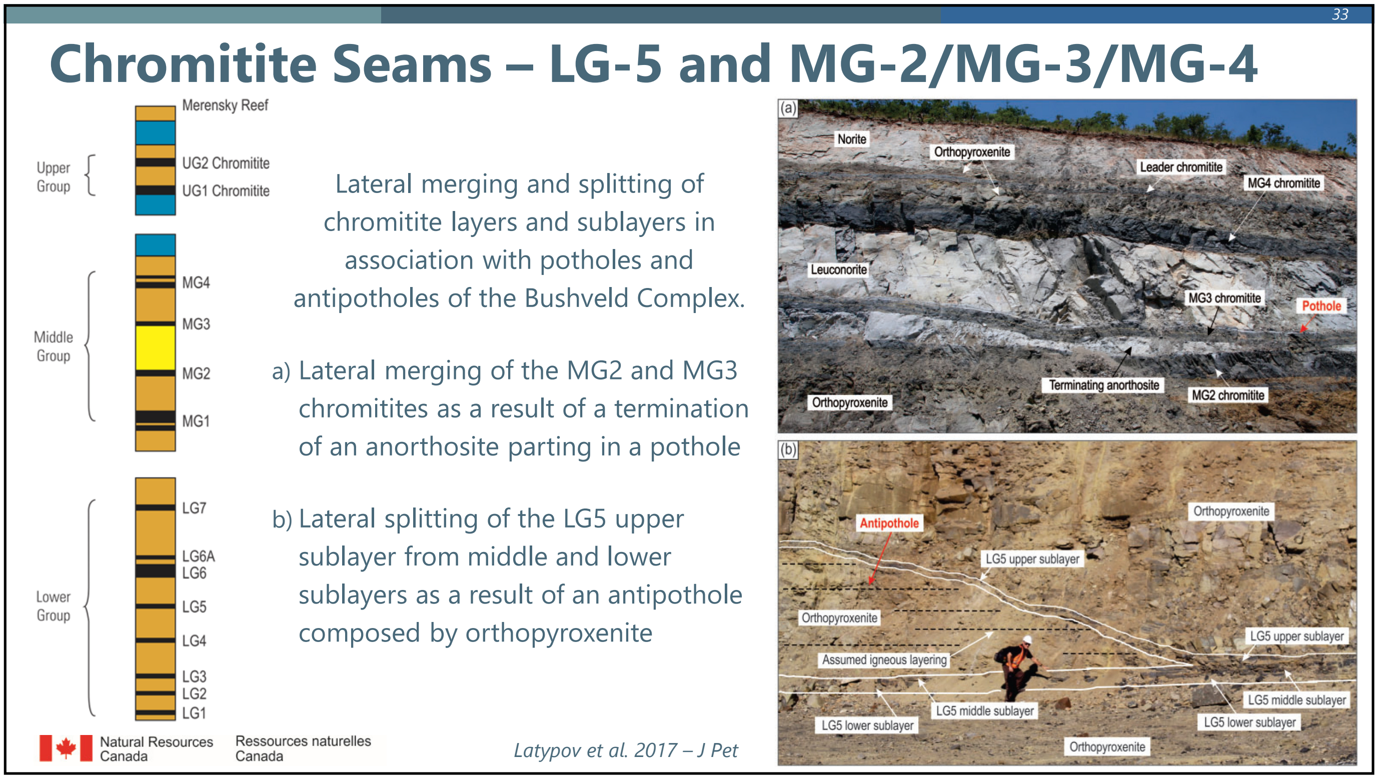
33
Chromitite Seams – LG-5 and MG-2/MG-3/MG-4
Merensky Reef
Upper Group
UG2 Chromitite
UG1 Chromitite
Middle Group
MG4
MG3
MG2
MG1
Lower Group
LG7
LG6A
LG6
LG5
LG4
LG3
LG2
LG1
Lateral merging and splitting of chromitite layers and sublayers in association with potholes and antipotholes of the Bushveld Complex.
a) Lateral merging of the MG2 and MG3 chromitites as a result of a termination of an anorthosite parting in a pothole
b) Lateral splitting of the LG5 upper sublayer from middle and lower sublayers as a result of an antipothole composed by orthopyroxenite
(a)
Norite
Orthopyroxenite
Leader chromitite
MG4 chromitite
Leuconorite
MG3 chromitite
Pothole
Terminating anorthosite
MG2 chromitite
Orthopyroxenite
(b)
Antipothole
Orthopyroxenite
LG5 upper sublayer
Orthopyroxenite
LG5 upper sublayer
Assumed igneous layering
LG5 middle sublayer
LG5 lower sublayer
LG5 middle sublayer
LG5 lower sublayer
Orthopyroxenite
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Latypov et al. 2017 – J Pet


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Chromitite Seams – UG-1 – Dwar's River Section
Merensky Reef
Upper Group
UG2 Chromitite
UG1 Chromitite
Middle Group
MG4
MG3
MG2
MG1
Lower Group
LG7
LG6A
LG6
LG5
LG4
LG3
LG2
LG1
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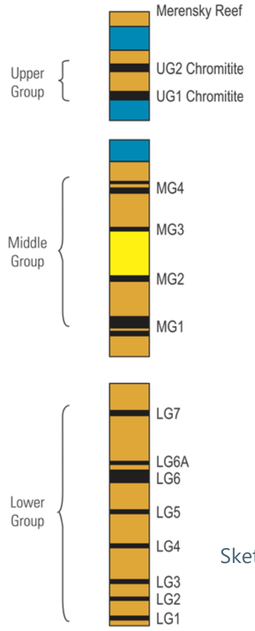
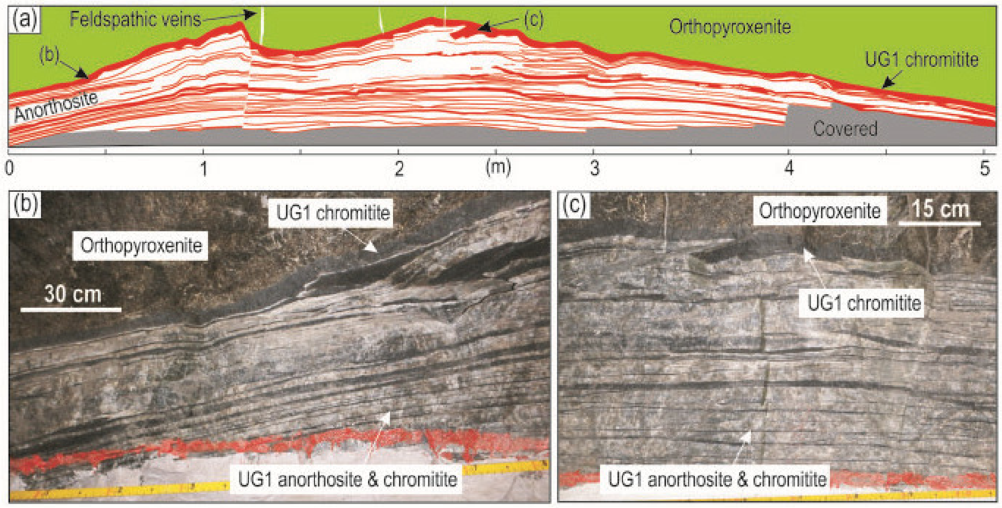
Chromitite Seams – UG-1 – Dwar's River Section





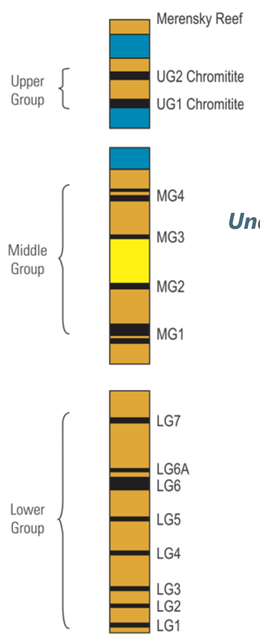
Sketch of a domal structure (a) with anorthosite–chromitite layering that is concordantly overlain by a thin UG1 chromitite layer. Photographs in (b) and (c) show UG1 chromitite and footwall rocks with anorthosite–chromitite layering

Natural Resources Canada Ressources naturelles Canada

Latypov et al. 2017 – J Pet

Canada

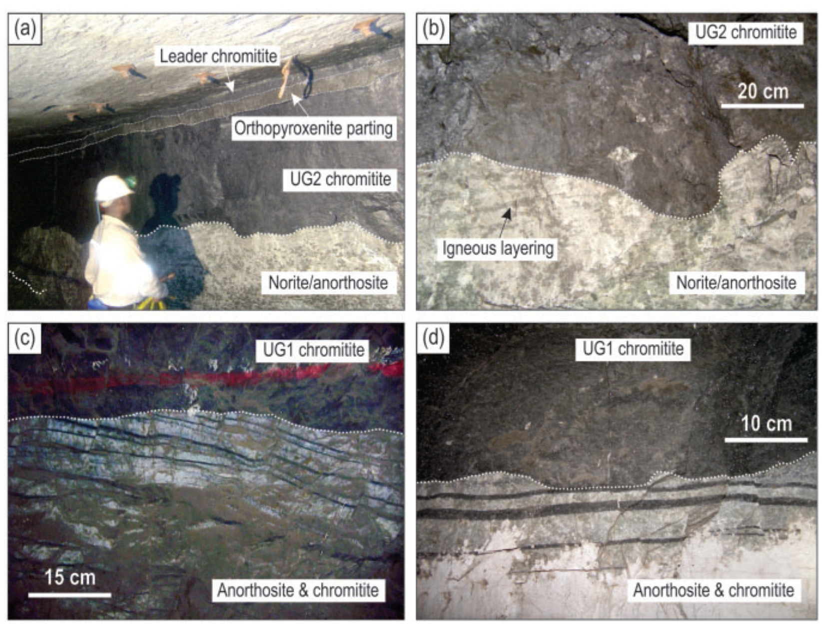
Chromitite Seams – UG-1 – Dwar's River Section



Undulating and scalloped lower contacts of chromitite layers

in the

Bushveld Complex.



Natural Resources Canada Ressources naturelles Canada

Latypov et al. 2017 – J Pet

Canada

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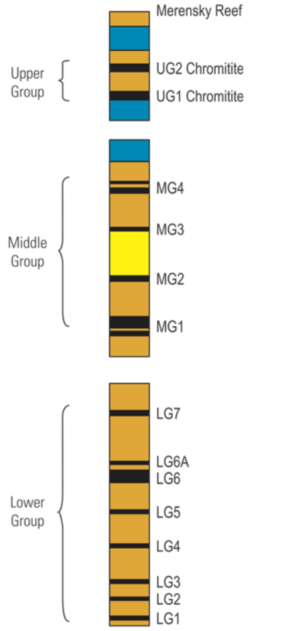
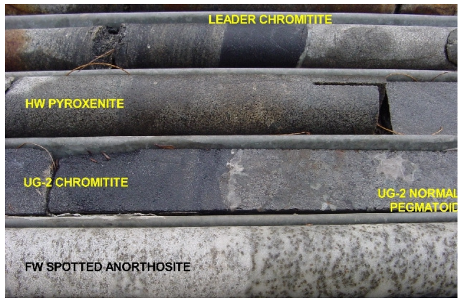
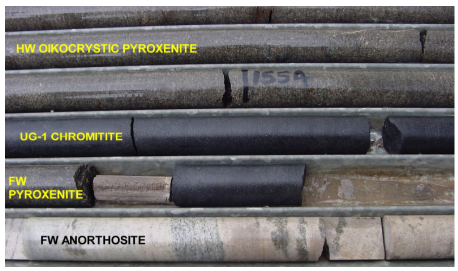
Chromitite Seams – UG-1 & UG-2 & MR

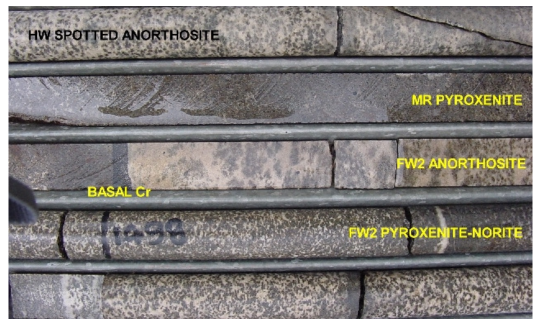




UG-2 Chromitite Seam



UG-1 Chromitite Seam



Basal Chromitite Seam of the Merensky Reef

Natural Resources Canada Ressources naturelles Canada

Photos from M. Lesher Canada

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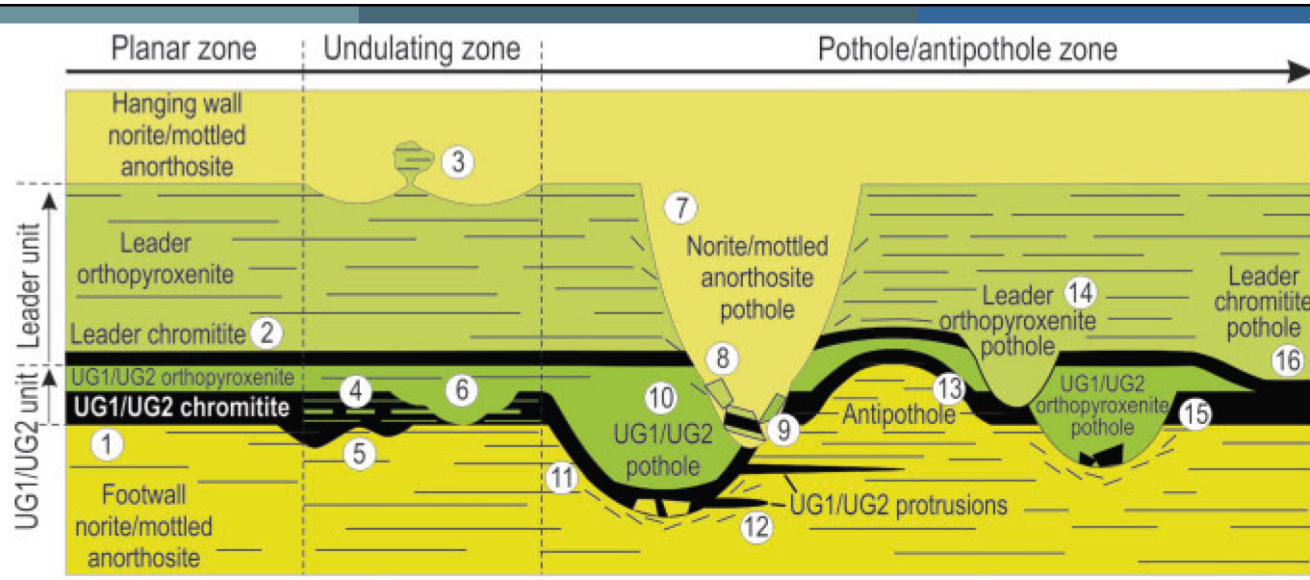

General summary of the most important field observations bearing on the origin of massive chromitite of the Bushveld Complex. The field observations are conditionally distributed to three domains referred to as planar, undulating and pothole/ antipothole zones

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Latypov et al. 2017 – J Pet Canada

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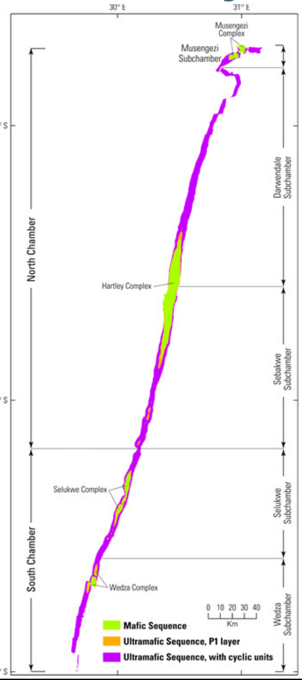
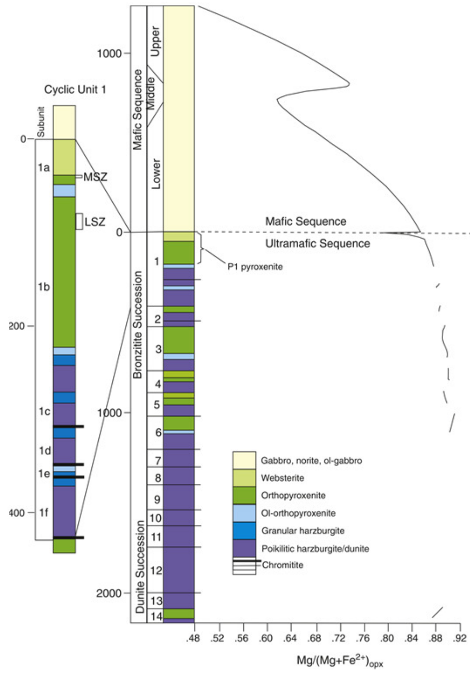
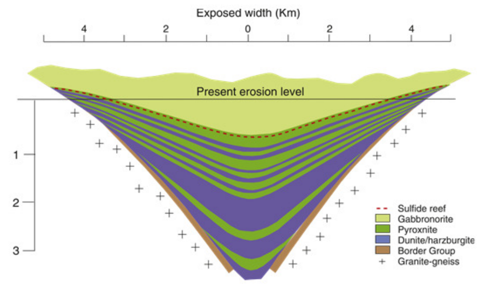
Great Dyke – Zimbabwe







Zientek et al. 2014; Maier et al. 2015 Canada

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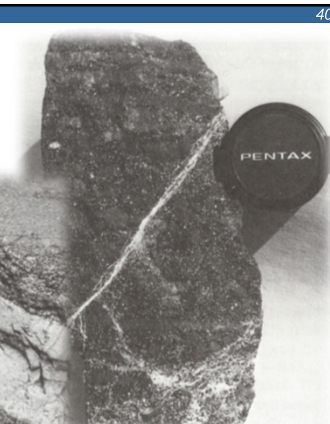
Great Dyke – Zimbabwe

	Upper Group Nos. 1–3 seams	*Lower Group Nos. 4–11 seams*
Bulk % Cr_2O_3	36–49	43–54
Bulk refractory ratio	2.8–3.2	3.9–4.4
Chromite Cr/Fe ratio	2.0–2.7	2.7–3.9
Friability at present mining depths	Ore lumpy to semifriable	No. 4 seam ± lumpy throughout. Nos. 5–11 seams highly friable with some lumpy ore
Form/thickness	Composite seams (up to 400 cm plus) comprising one or more massive to disseminated layers each 5–100 cm thick	Single seams 10–15 cm thick
Wall rocks/mining conditions	Harzburgite wall rocks (except footwall pyroxenite of No. 2 seam). Serpentinized form relatively hard; good ground conditions but jackhammers required	Dunite wall rocks (except footwall pyroxenite of No. 4 seam). Serpentinized form vcry soft; poor ground conditions but suitable for electric coal drills. No. 4 seam requires jackhammers and special extraction techniques.

Source: Chemical data summarized from Slatter, 1980*a*, 1980*b*.
Notes: Bulk refractory ratio: (Cr_2O_3 + MgO + Al_2O_3)/(total Fe as FeO + SiO_2) from Slatter, 1981. Upper and Lower Group seams best known, respectively, in southern and northern parts of Hartley Complex.

Massive chromitite showing weak nodular texture No. 2 seam



Three layered Olivine-Chromite seams separated by harzburgite

No. 2 seam

Natural Resources Canada Ressources naturelles Canada

Prendergast 1987 – Evolution of Chromium Ore Fields Canada

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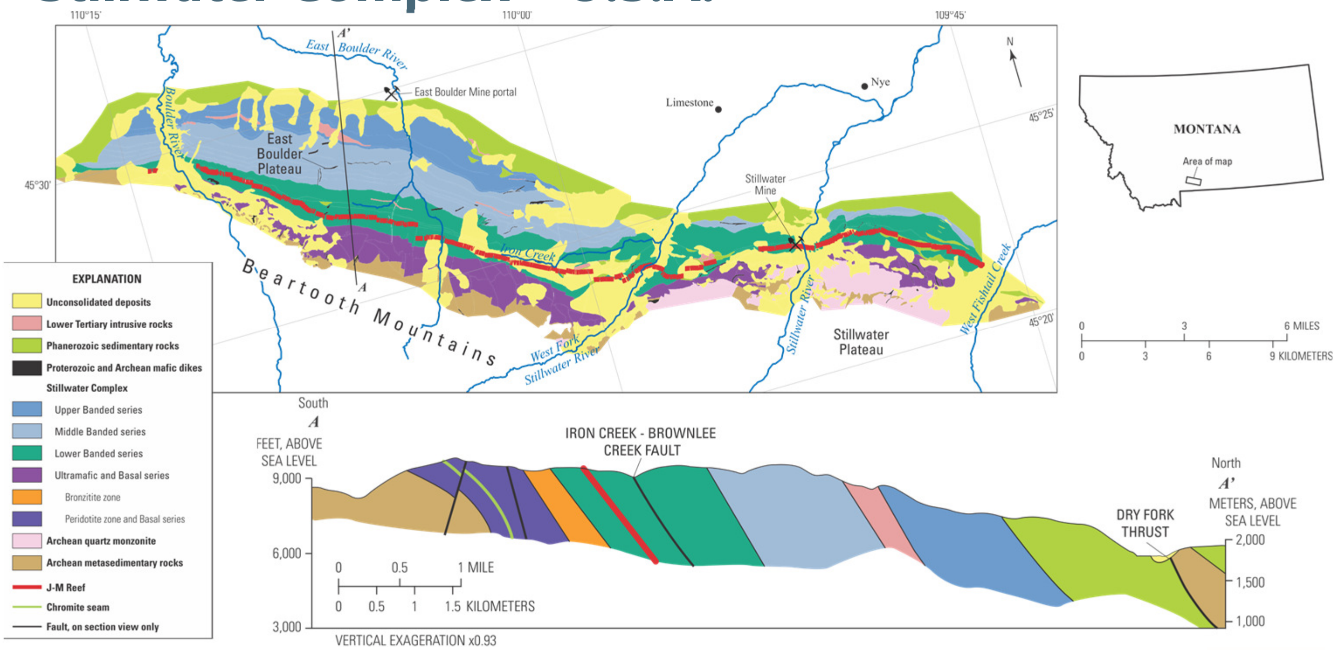
Stillwater Complex – U.S.A.



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Zientek & Parks 2014 – USGS Canada

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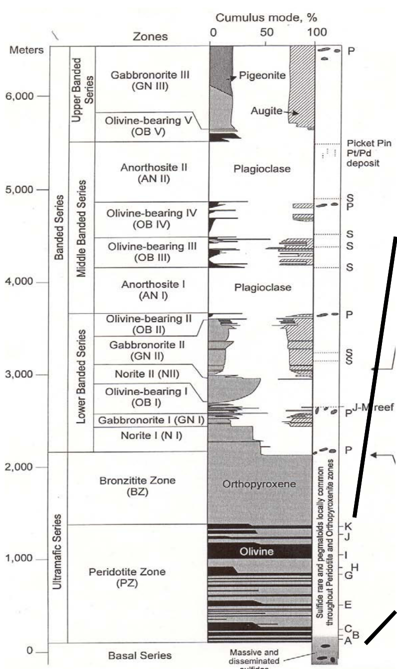
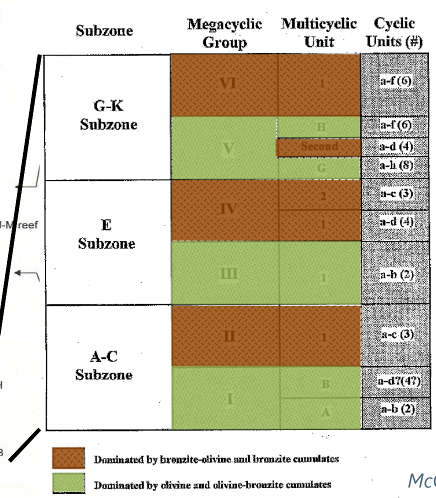
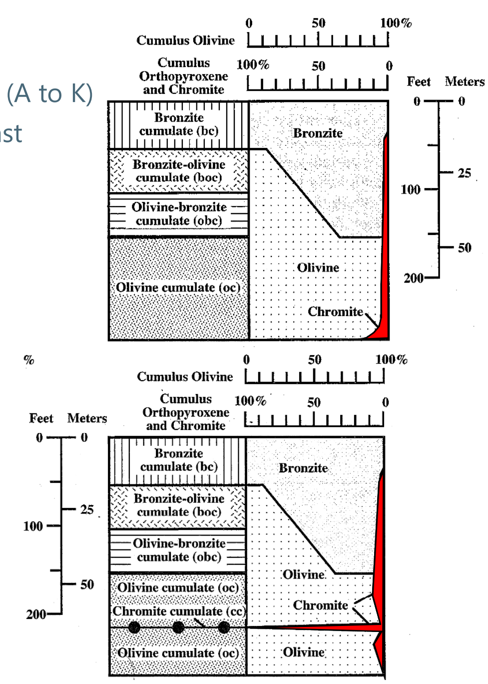
Stillwater Complex – U.S.A.

- Contain up to 9 chromitite seams (A to K)
- G & H have been mined in the past
- All within the Ol-rich ultramafic component of the complex







McCallum 2002; Cooper 2002 – 9th IPS Guidebook Canada

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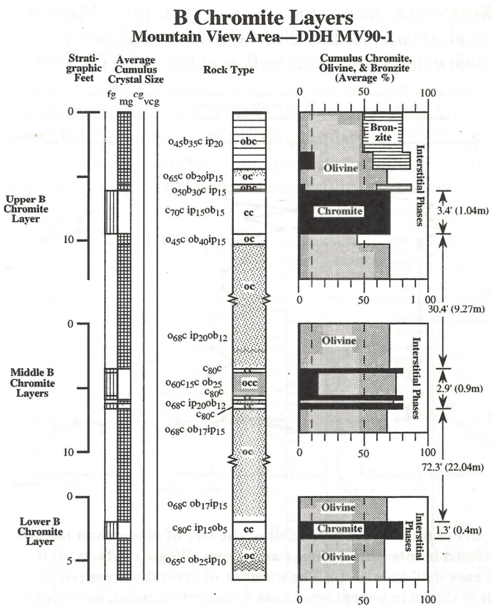
B Chromitite Layer



B Chromitite include various chromitite layers

- **Lower B:** Consist of a single massive Chrt layer (~0.4m) with sharp upper & lower contacts
- **Middle B:** Consist of 3 Chrt layers interleaved with with Oc or chr Oc
  - Lowermost (12 cm): Sharp upper and lower contacts
  - Second (9 cm): Sharp lower and diffuse to gradational upper contacts
  - Upper (12 cm): Gradational to irregular lower contact and sharp upper contact
- **Upper B:** Consist of a single massive Chrt layer (~1.04m) with sharp upper and lower contacts

Cooper 2002 – 9th IPS Stillwater Guidebook

Natural Resources Canada Ressources naturelles Canada Canada

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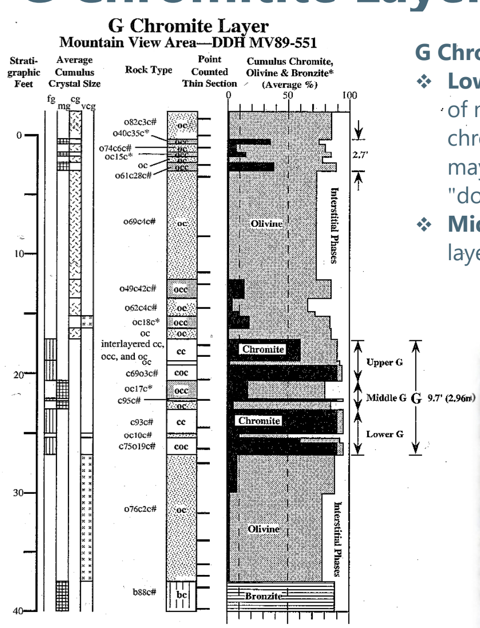
G Chromitite Layer



G Chromitite include various chromitite layers

- **Lower and Upper G:** Consist of two intervals of near massive (50-85%) to massive (+85%) chromite interleaved by an interval of Oc that may contain 5 to 25% chromite producing a "doublet" pattern
- **Middle G:** Consist of a very thin massive Chrt layer within a chr-bearing Oc

Cooper 2002 – 9th IPS Stillwater Guidebook

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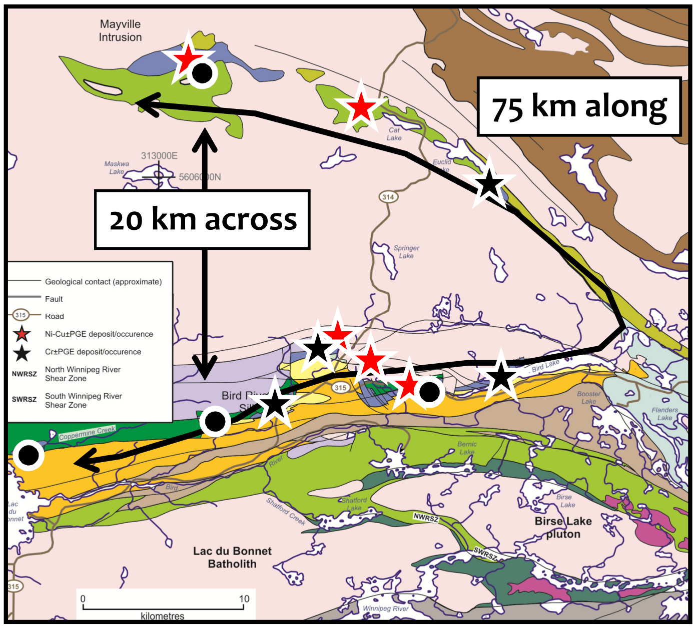
Bird River Sill – Manitoba, Canada



- ❖ Large M-UM magmatic event in the BRGB
- ❖ Across the entire belt
- ❖ Good mineral endowment
- ❖ Ni-Cu magmatic sulfide deposits
- ❖ Cr-PGE deposits

Houlé et al. 2013 – GAC MAC Presentation

Natural Resources Canada | Ressources naturelles Canada | Canada

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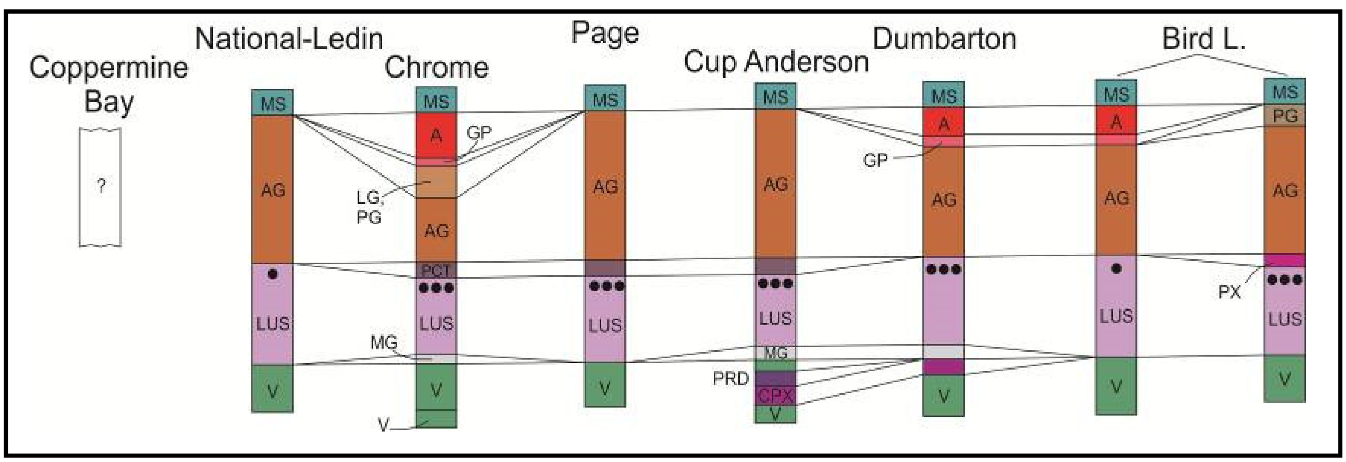
Bird River Sill – Manitoba, Canada



Bannatyne and Trueman 1982

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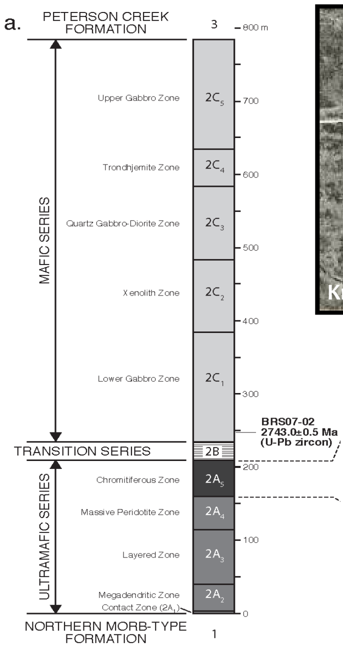
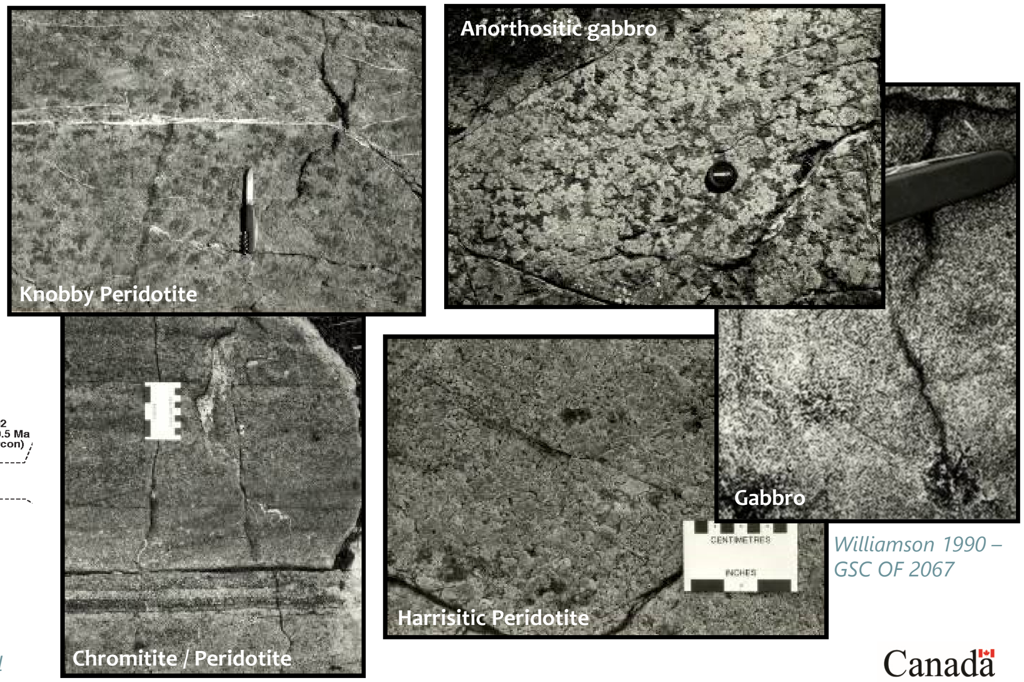
Chrome Intrusion – Bird River Sill



Scoates & Scoates 2013 – Econ Geol



Williamson 1990 – GSC OF 2067

Canada

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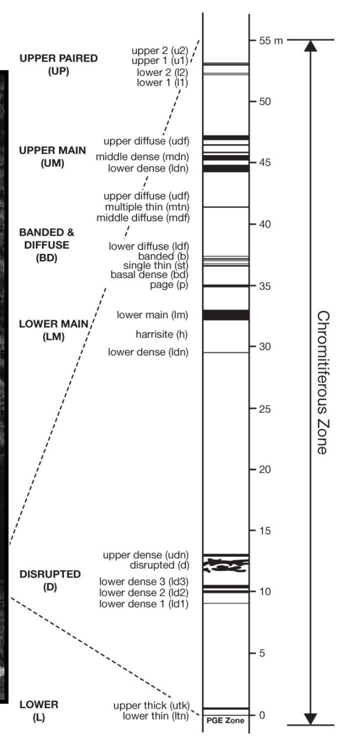
Chrome Intrusion – Bird River Sill



Williamsons 1990 – GSC OF 2067

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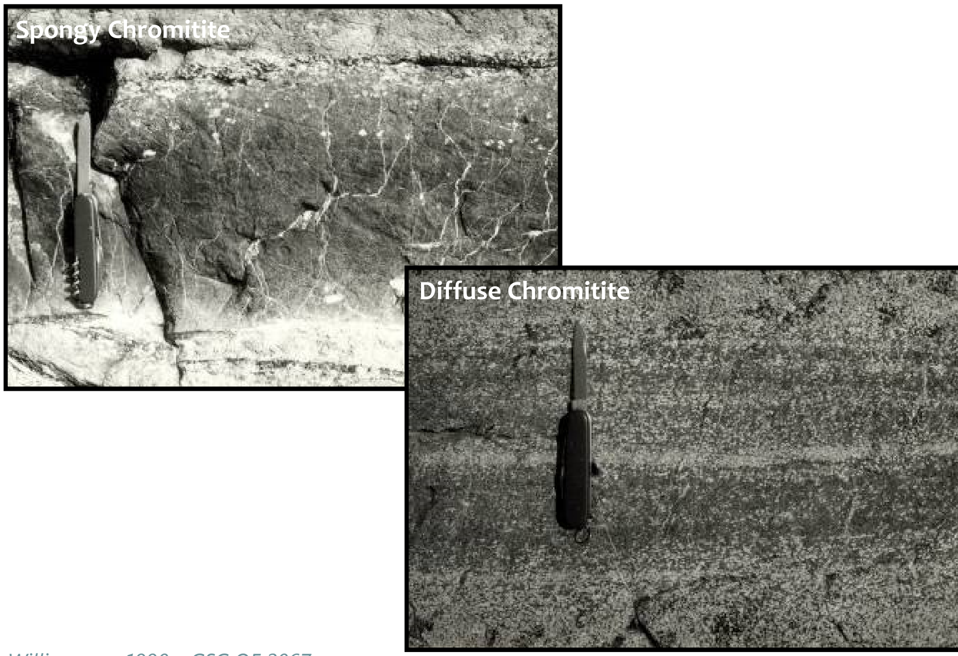
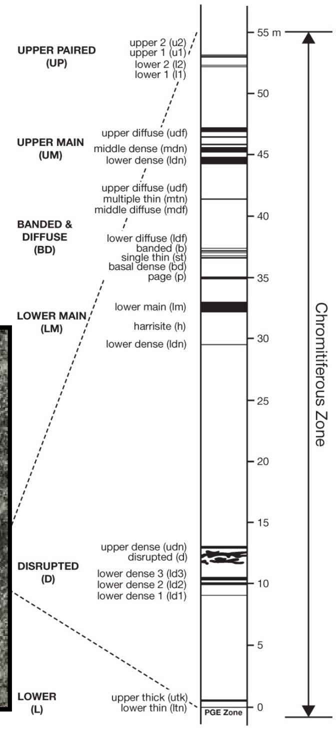
Chrome Intrusion – Bird River Sill





Williamsons 1990 – GSC OF 2067

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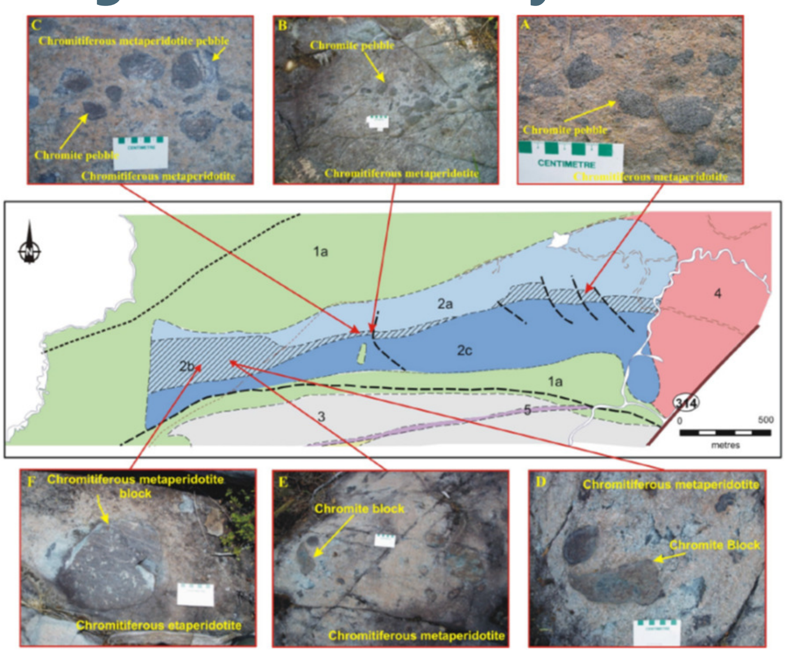
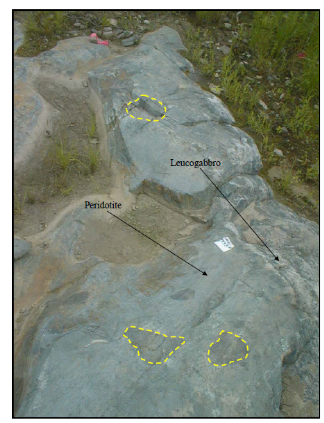
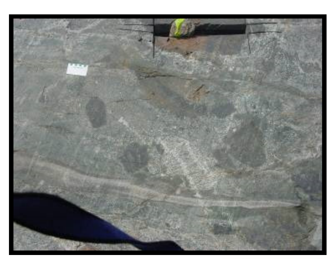
Page Intrusion / Mayville Intrusion



Page Intrusion

Mayville Intrusion





Mealin 2008 – MSc hesis / Hiebert 2003 – BSc Thesis

Canada

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Stratiform Chromite Deposit (Type IA-IB)

Chromite deposits are typically divided into two main types: Stratiform and Podiform. Stratiform deposits can be further subdivided into:

- ***Large post-Archean layered intrusion-hosted deposits that represent periodically-replenished magma chambers*** (e.g., Bushveld Complex, South Africa; Stillwater Complex, USA) ***formed from silicious high-Mg basaltic magmas***

- ***Small-intermediate-sized Archean conduit-hosted deposits that represent flow-through magma systems*** (e.g., Kemi, Finland; Inyala and Railway Block, Zimbabwe; Ipueira-Medrado, Brazil; Sukinda, India; Nkomati, South Africa; Black Thor-Blackbird, Canada) ***formed from low-Mg komatiitic magmas***

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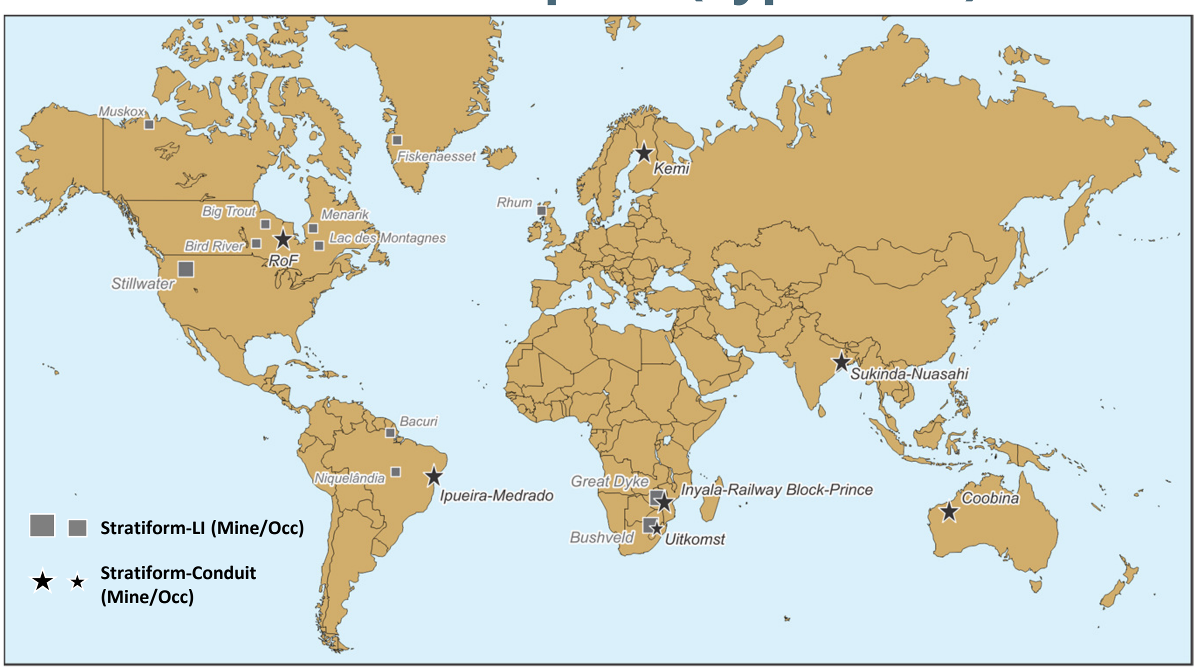
Stratiform Chromite Deposit (Type IA-IB)



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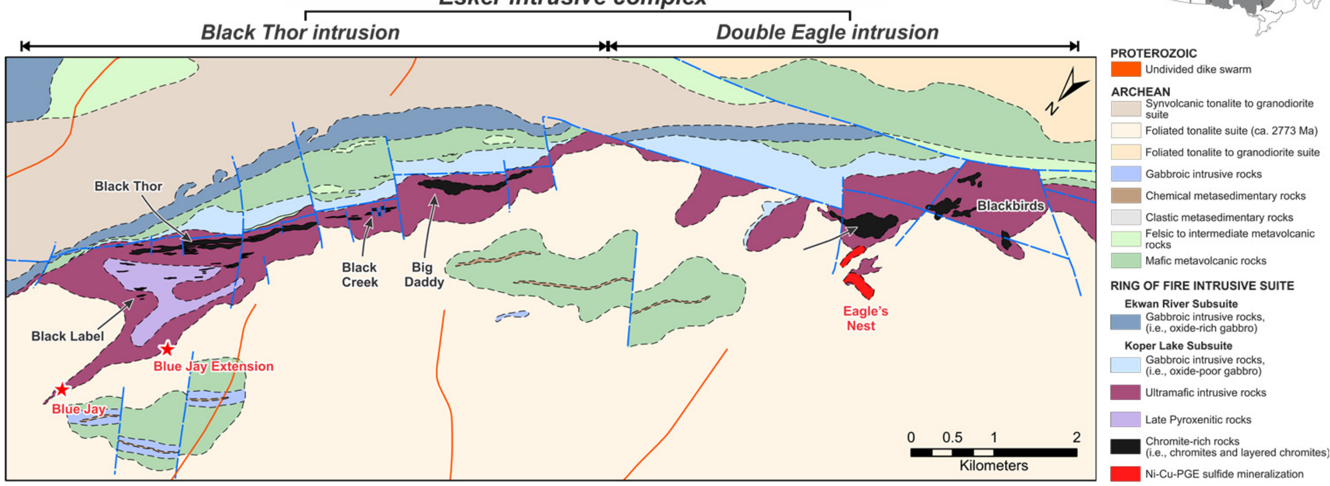
Black Thor/Double Eagle Intrusions - Canada

- Archean (ca. 2734 Ma) komatiitic intrusion occurring in the Superior Province
- Composed the Esker Intrusive Complex (EIC), an ultramafic-dominated complex
- Exposed over a strike length of ~15 km x ~3 km and host world-class chromite deposits



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Houlé et al. 2019 – GSC OF

Canada

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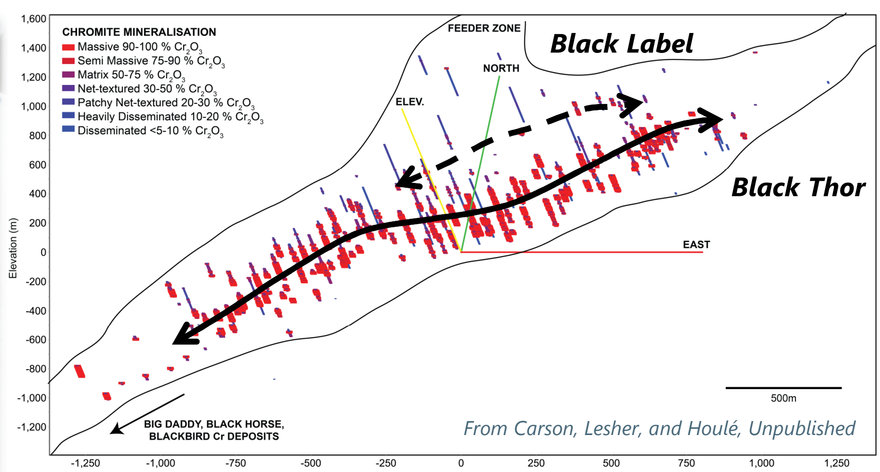
Cr_2O_3 Distribution - Black Thor Intrusion

Black Thor Massive Chromitite
74 m Chromite Intersection



From Carson, Lesher, and Houlé, Unpublished

- Black Thor deposit is very continuous whereas Black Label is dismember by the late websterite phase…
- Large accumulation of chromite into a relatively small intrusion that require a vast volume of magma (i.e., magmatic conduit)

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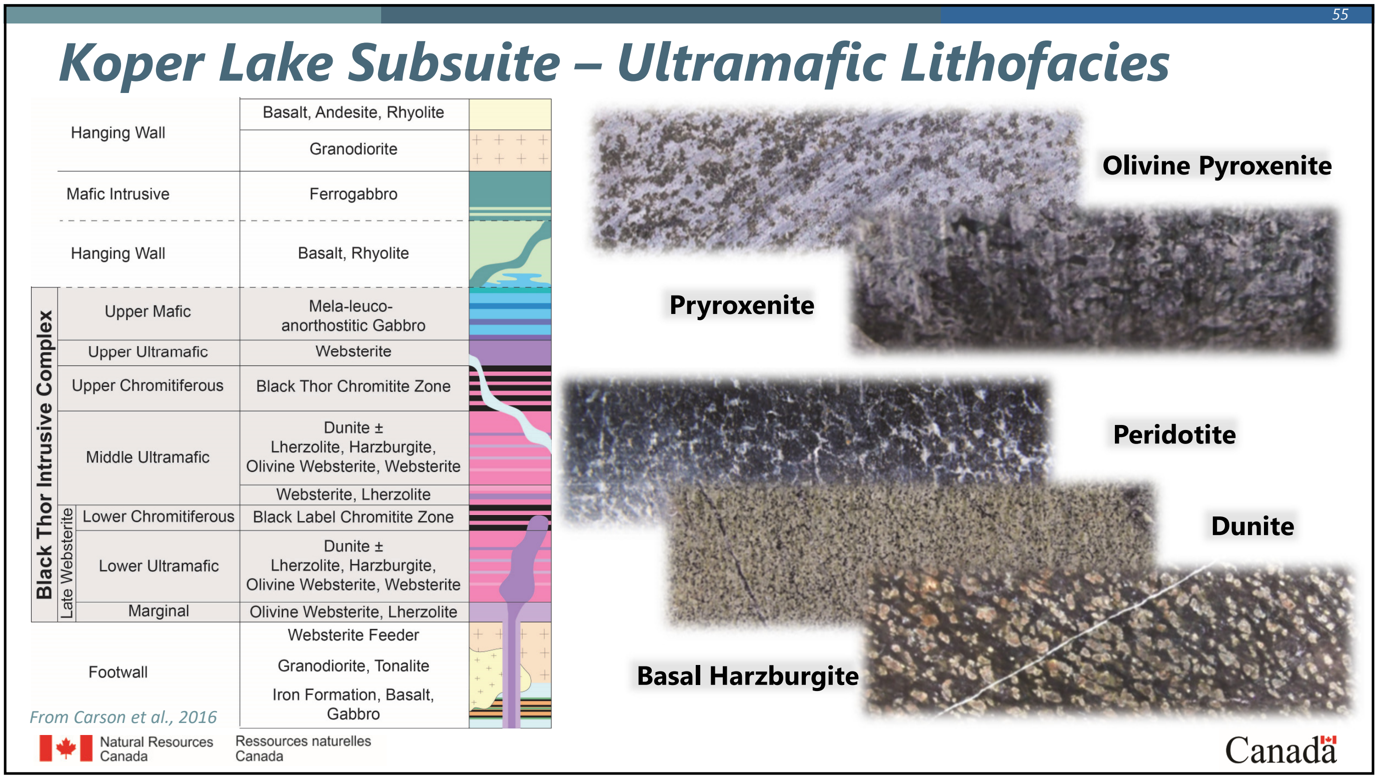
Canada


55
Koper Lake Subsuite – Ultramafic Lithofacies
Hanging Wall
Basalt, Andesite, Rhyolite
Granodiorite
Mafic Intrusive
Ferrogabbro
Hanging Wall
Basalt, Rhyolite
Black Thor Intrusive Complex
Late Websterite
Upper Mafic
Mela-leuco-anorthositic Gabbro
Upper Ultramafic
Websterite
Upper Chromitiferous
Black Thor Chromitite Zone
Middle Ultramafic
Dunite ± Lherzolite, Harzburgite, Olivine Websterite, Websterite
Websterite, Lherzolite
Lower Chromitiferous
Black Label Chromitite Zone
Lower Ultramafic
Dunite ± Lherzolite, Harzburgite, Olivine Websterite, Websterite
Marginal
Olivine Websterite, Lherzolite
Footwall
Websterite Feeder
Granodiorite, Tonalite
Iron Formation, Basalt, Gabbro
From Carson et al., 2016
Olivine Pyroxenite
Pryroxenite
Peridotite
Dunite
Basal Harzburgite
Natural Resources Canada
Ressources naturelles Canada
Canada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Koper Lake Subsuite – Ultramafic Lithofacies
Hanging Wall
Basalt, Andesite, Rhyolite
Granodiorite
Mafic Intrusive
Ferrogabbro
Hanging Wall
Basalt, Rhyolite
Black Thor Intrusive Complex
Late Websterite
Upper Mafic
Mela-leuco-anorthositic Gabbro
Upper Ultramafic
Websterite
Upper Chromitiferous
Black Thor Chromitite Zone
Middle Ultramafic
Dunite ± Lherzolite, Harzburgite, Olivine Websterite, Websterite
Websterite, Lherzolite
Lower Chromitiferous
Black Label Chromitite Zone
Lower Ultramafic
Dunite ± Lherzolite, Harzburgite, Olivine Websterite, Websterite
Marginal
Olivine Websterite, Lherzolite
Footwall
Websterite Feeder
Granodiorite, Tonalite
Iron Formation, Basalt, Gabbro
From Carson et al., 2016
Natural Resources Canada
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Canada

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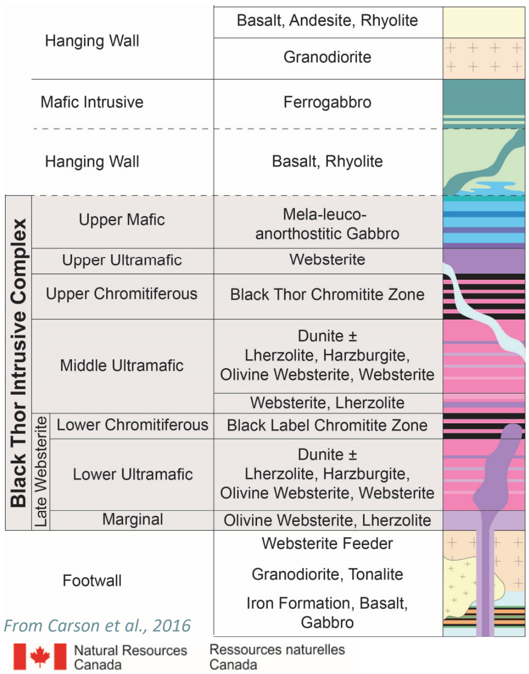
Koper Lake Subsuite – Mafic Lithofacies



From Carson et al., 2016

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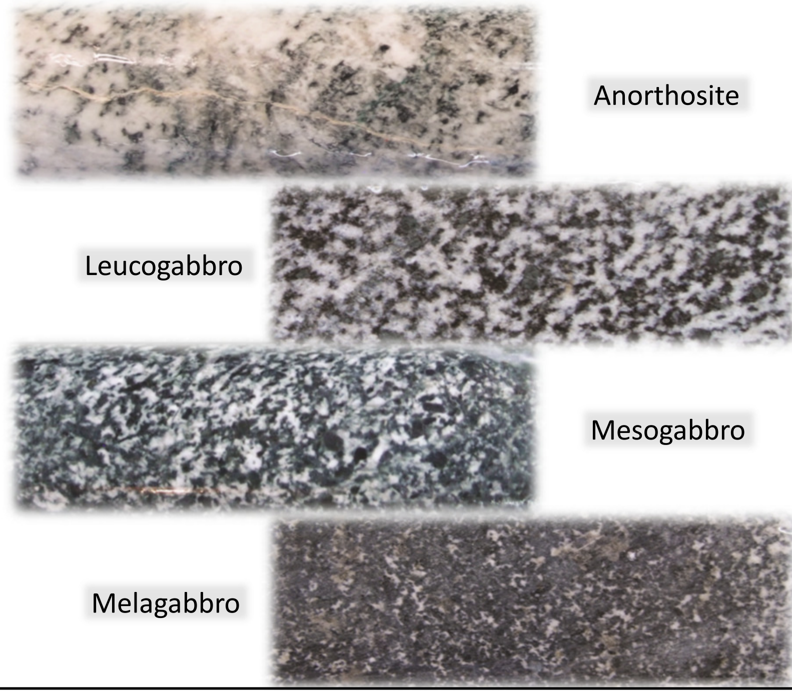

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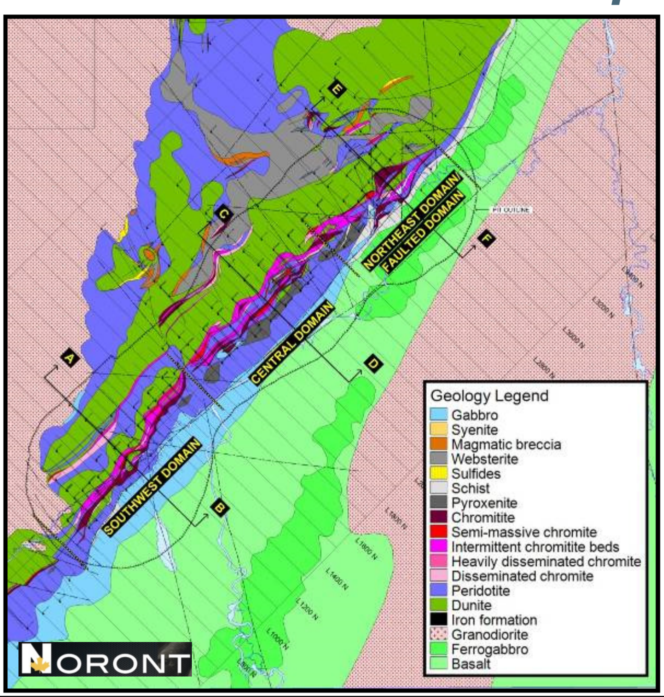
Black Thor-Black Label Deposits – Black Thor intrusion



- **Ore envelop is ~45m & ~70m thick**
- **2 main mineralized zones**
  - Black Thor (top)
  - Black Label (bottom)
- **Ore location**
  - At the contact dunite-peridotite / pyroxenite zones
  - Middle of dunitic zone
- **Chromite textural facies**
  - Massive chromitite
  - Semi-massive chromitite
  - Banded chromitite
  - Disseminated chromite

Canada

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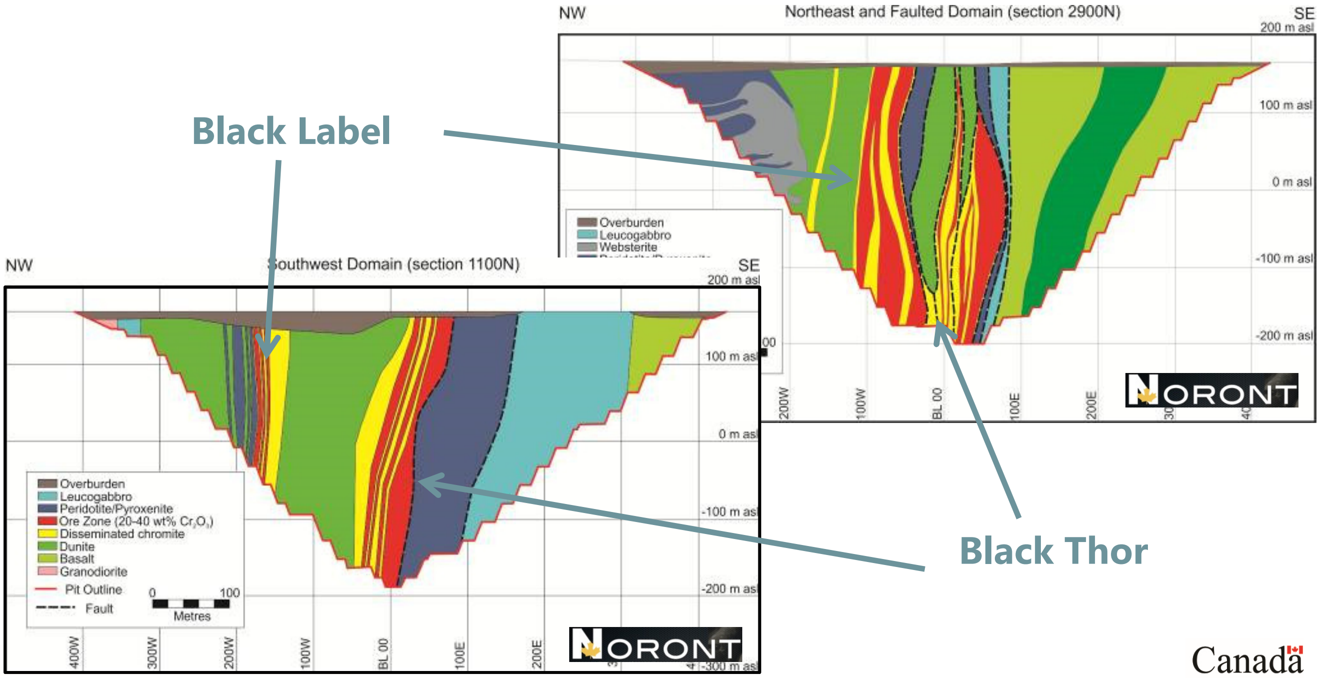
Black Thor-Black Label Deposits – Black Thor intrusion



Canada

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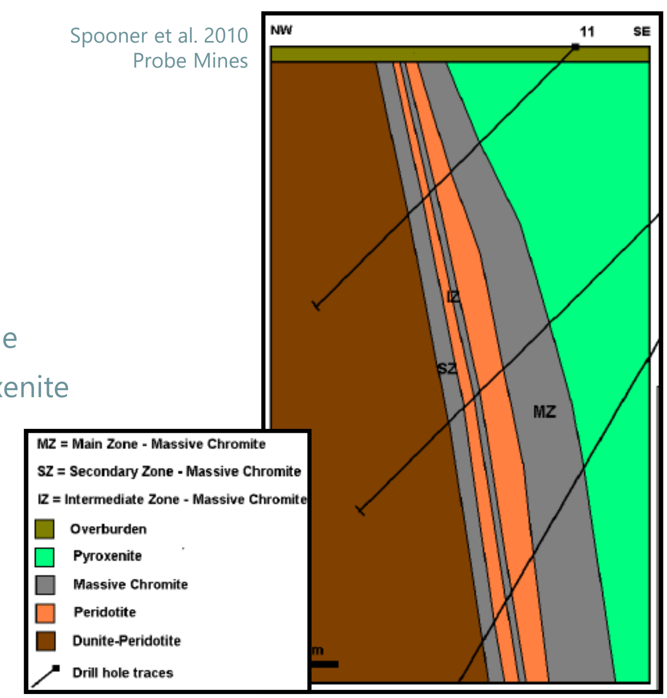
Black Creek Deposit – Black Thor intrusion

- ❖**Ore envelop is ~65m thick**
- ❖**3 main mineralized zones**
  - ❖ Main Zone (top)
  - ❖ Intermediate Zone
  - ❖ Secondary Zone (bottom)
- ❖**Ore location**
  - ❖ Upper part of the dunite-peridotite zone
  - ❖ At the contact dunite-peridotite / pyroxenite zones
- ❖**Chromite textural facies**
  - ❖ Massive chromitite
  - ❖ Semi-massive chromitite
  - ❖ Banded chromitite
  - ❖ Disseminated chromite

Spooner et al. 2010
Probe Mines



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Black Creek Deposit – Black Thor intrusion

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Canada

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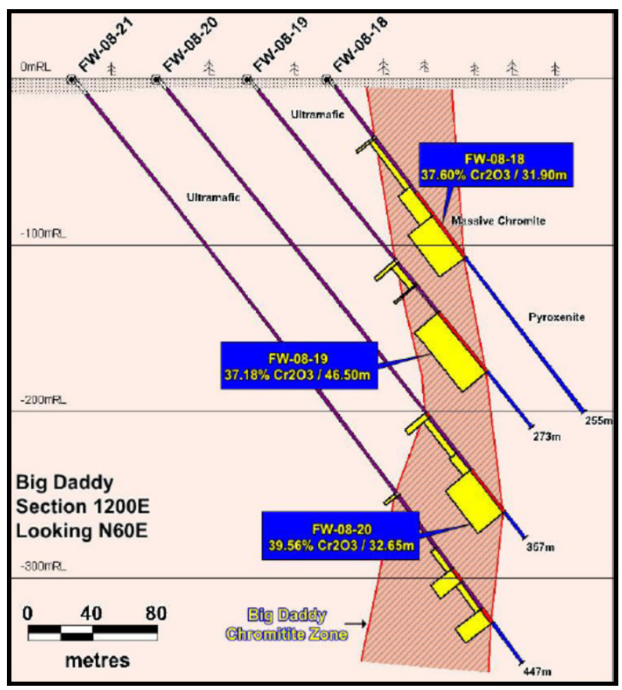
Big Daddy Deposit – Black Thor intrusion

- **Ore envelop is ~45m thick**
- **2 main mineralized zones**
  - BD1 & BD2 (~same stratigraphic level)
- **Ore location**
  - Upper part of the dunite-peridotite zone
  - At the contact dunite-peridotite / pyroxenite zones
- **Chromite textural facies**
  - Massive chromitite, dominated
  - Semi-massive chromitite
  - Banded chromitite
  - Disseminated chromite



KWG Resources corporate presentation

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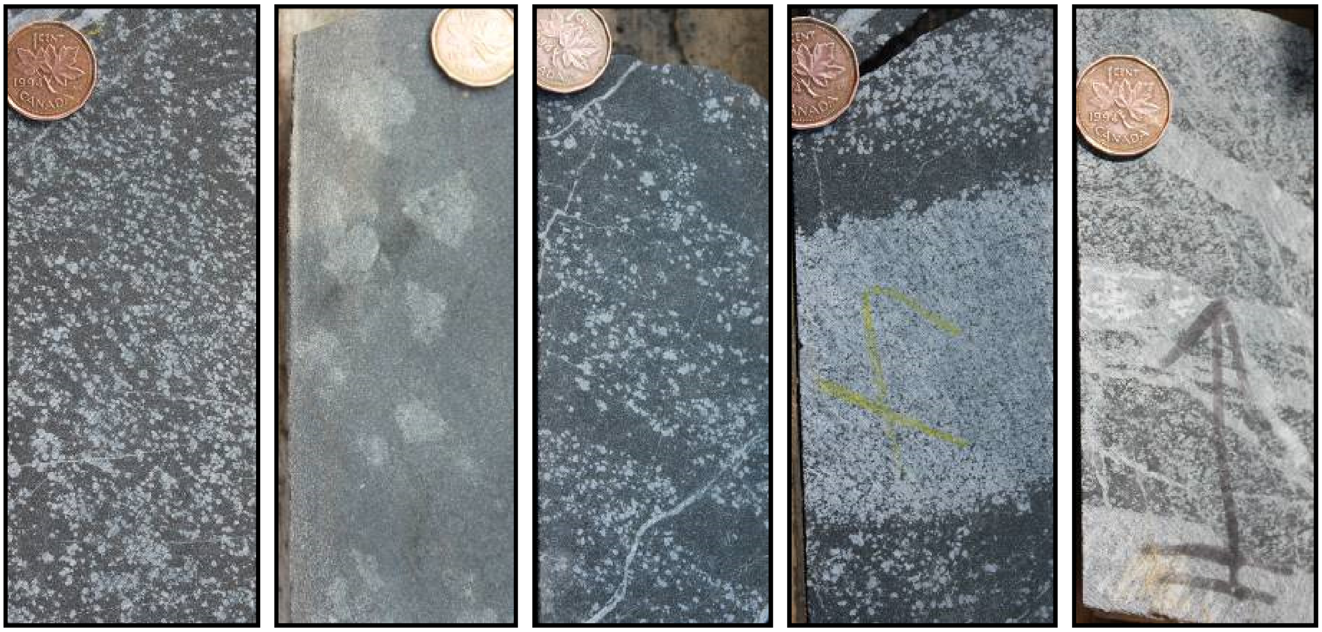
Big Daddy Deposit – Black Thor intrusion



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Canada

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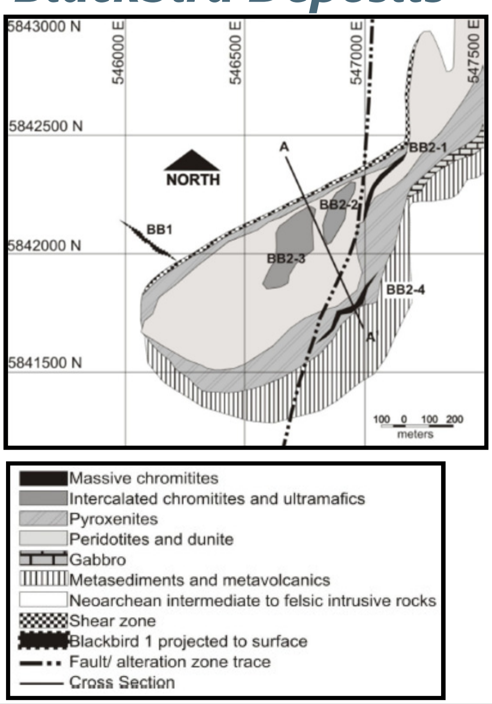
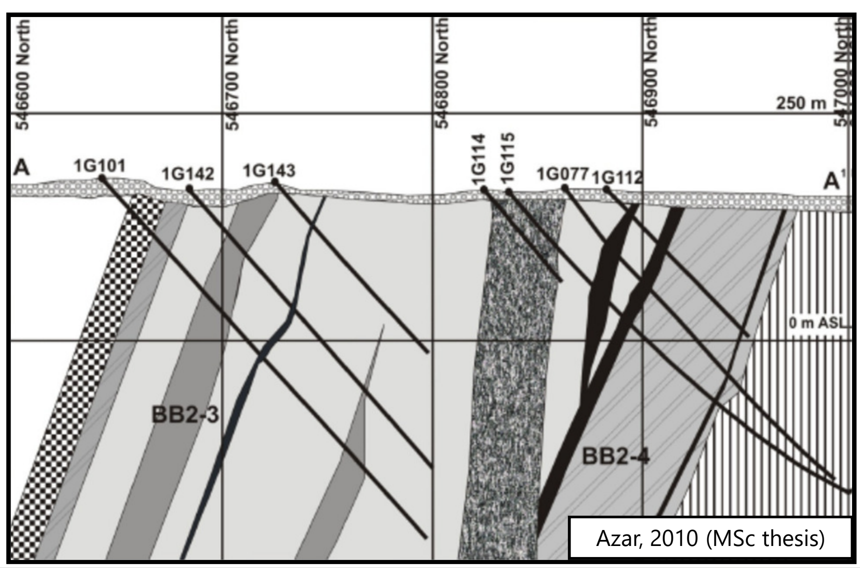
Blackbird Deposits – Double Eagle intrusion



- 4 main mineralized zones
  - BB1, BB2-1 & BB2-4 : Massive ores
  - BB2-2 & BB2-3 : Banded ores



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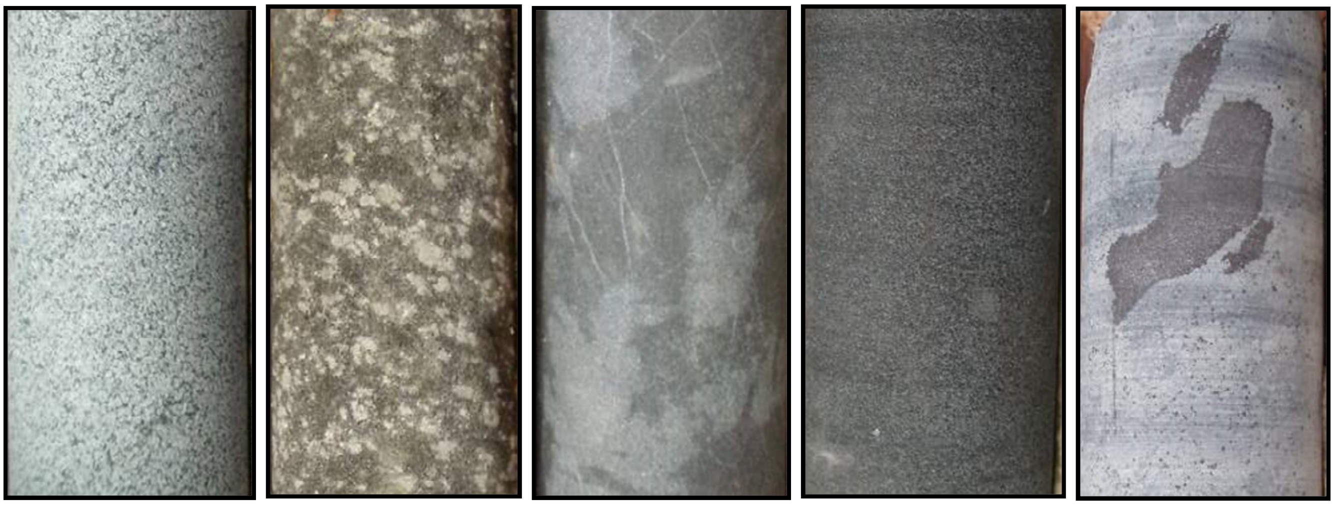
Blackbird Deposits – Double Eagle intrusion



Diss. Chr w/ Dnt | SM Chrt | M Chrt w/ Opx ghosts | Massive Chrt | Chrt clast w/ Prd

Azar, 2010 (MSc thesis)

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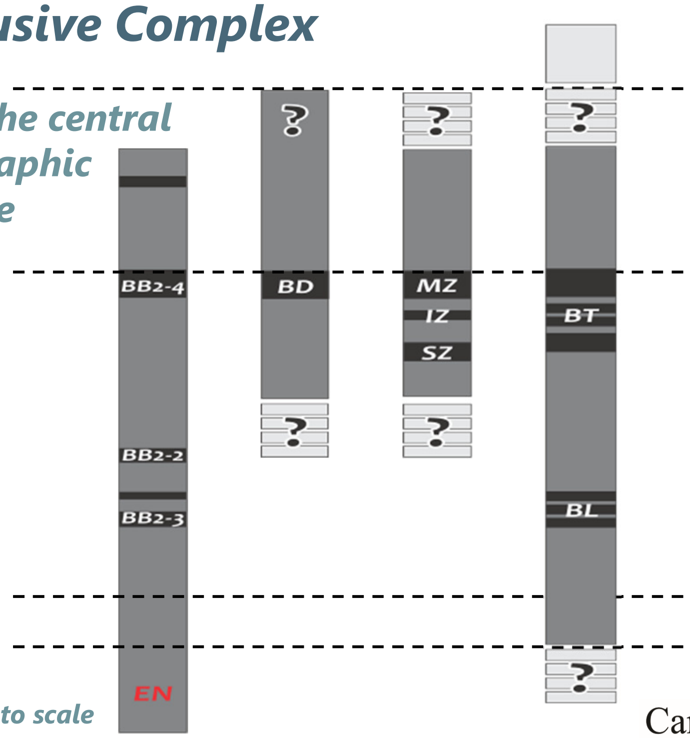
Chromitites – Esker Intrusive Complex

Well-mineralized complex in the central part exhibit some stratigraphic variations along strike

- ❖Proximal versus distal facies variations;
- ❖Different intrusions involved;
- ❖Post-magmatic modification (later injection of granoitoids)



Not to scale

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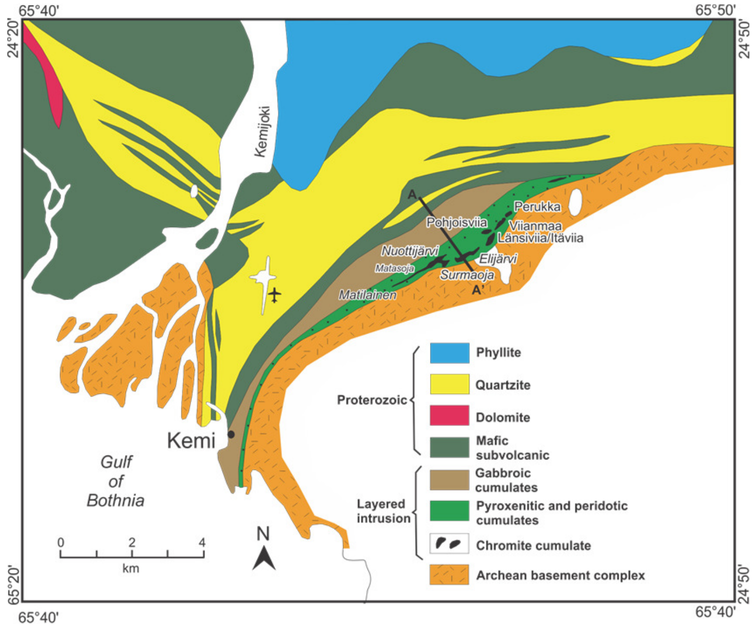
Kemi Intrusion - Finland



- ❖ Differentiated layered intrusion, ~22 km long and ~0.2 to 2km wide
- ❖ Consists of several ore bodies over a length of ~3 km

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Huhtelin 2015 – Mineral Deposits of Finland Canadä

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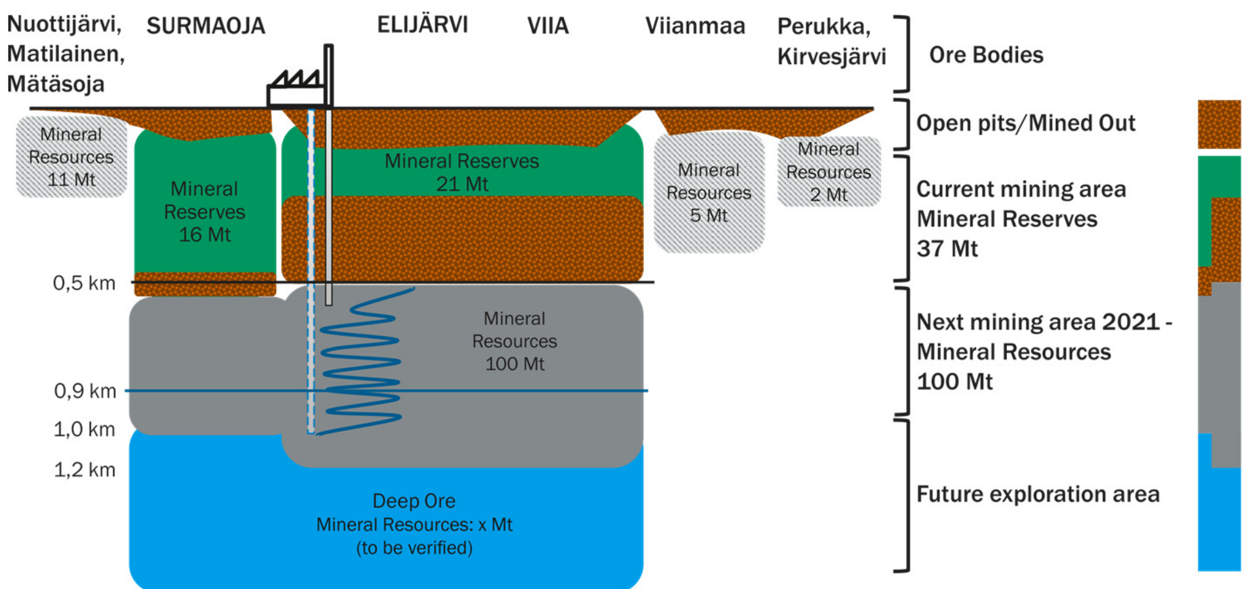
Kemi Intrusion - Finland



Classification according to Fennoscandian Review Board standard (FRB). January 1st, 2018.

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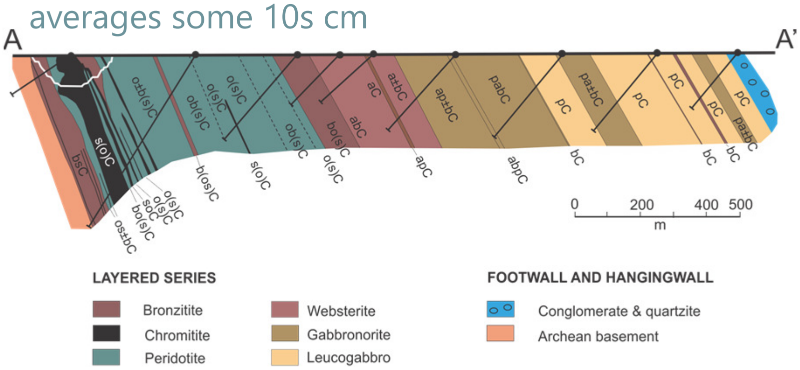
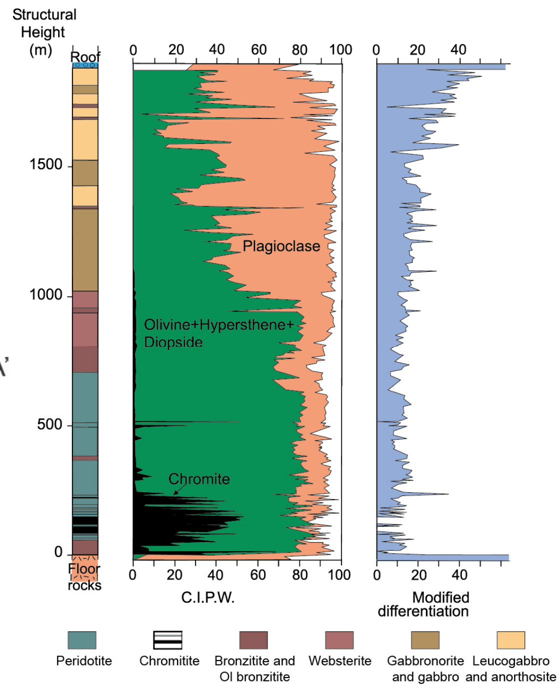
Kemi Intrusion - Finland

- Lower Ultramafic & an Upper Gabbroic part
  - Central part is the thickest and become thinner toward the ends (~1000m thick UM & ~900m thick M)
- Chromite ore average width of 40m, locally reaching a thickness of well over 100m
- In both ends, the thickness of the chromitite layer averages some 10s cm





Huhtelin and Alapieti 2005 – 10th IPS Guidebook

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Kemi Intrusion - Finland

Rounded to subrounded chromitite clasts ("pebbles") within a talc-carbonate ultramafic rock with heavily disseminated chromite matrix

Huhtelin 2015 – Mineral Deposits of Finland

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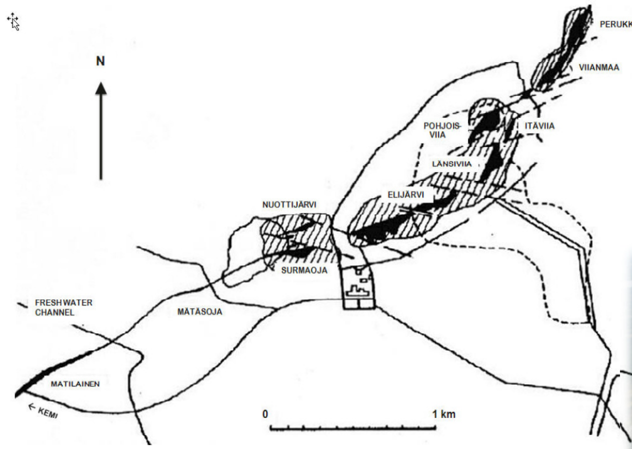
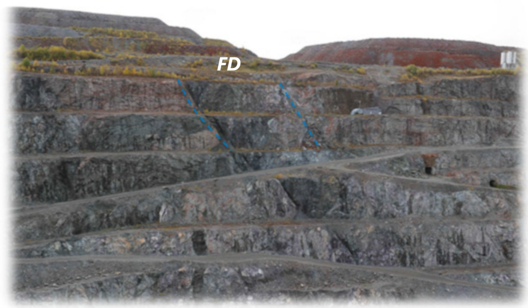
Kemi Intrusion - Finland





- Distribution of the chromite ore bodies at Kemi
- Aerial view of the mining area with the approximate contacts of the main lithological units
- View of the feeder dike on the southern wall of the active open pit

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Modified after Huhtelin 2015 – Mineral Deposits of Finland

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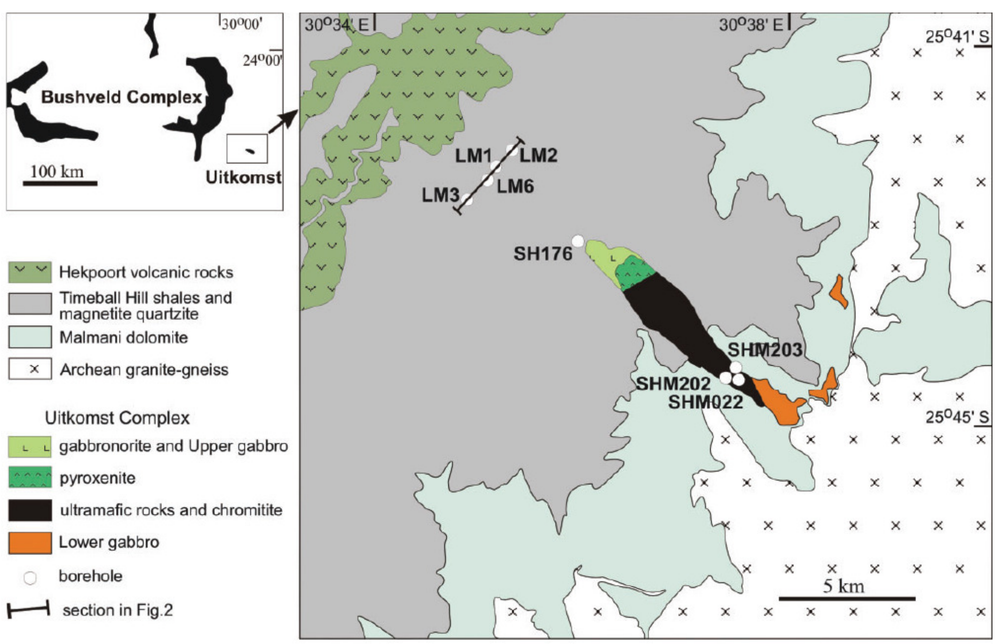
Uitkomst Intrusion – South Africa



Uitkomst Complex is interpreted to be part of the Bushveld event

- Broadly similar lithologies
- Mineral compositions in the intrusions
- Geochronology U-Pb zircon 2057.64 ± 0.69

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Yudovskaya et al. 2015 / Maier et al. 2018 – J. Pet. / Mineral Deposita

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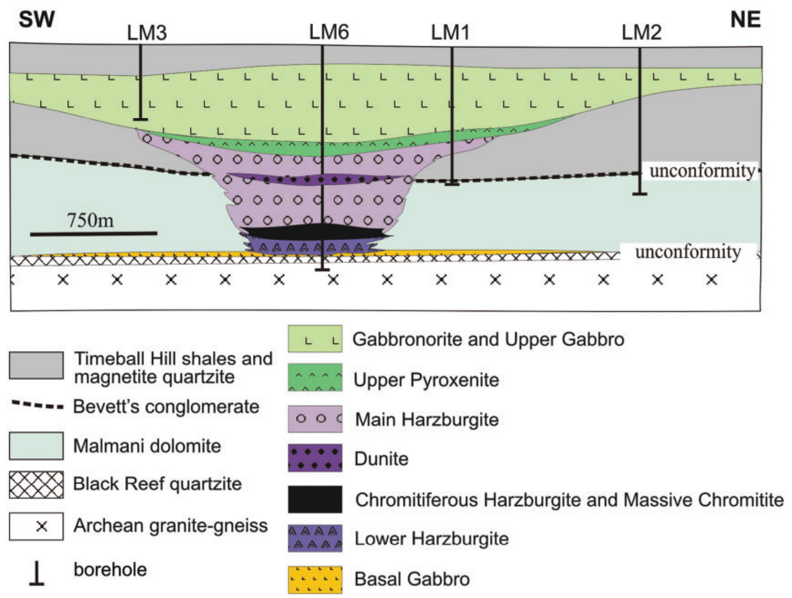
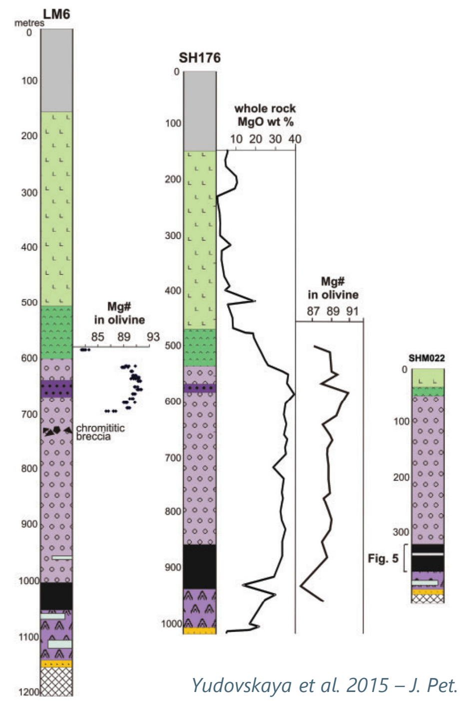
Uitkomst Intrusion – South Africa





Yudovskaya et al. 2015 – J. Pet.

Uitkomst Intrusion – South Africa

Main chromitite layer within the main open pit at the Uitkomst Complex

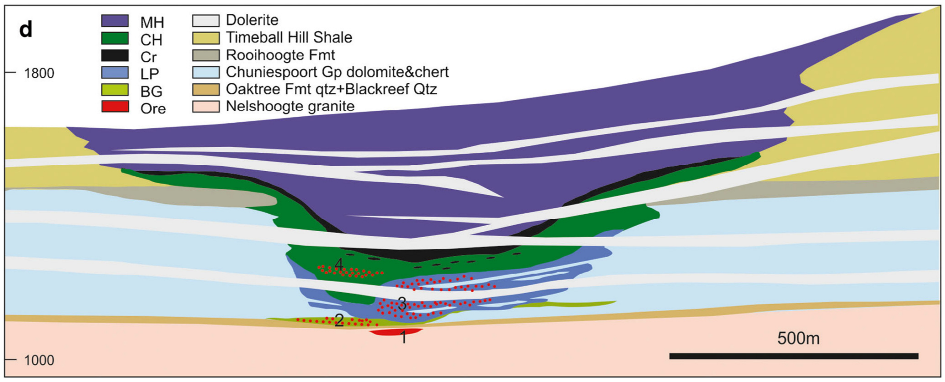
Maier et al. 2018 – Mineral Deposita

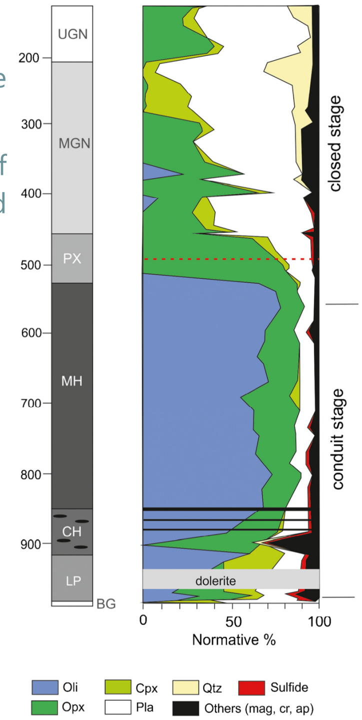
Layered massive chromitite layers & thin cm-scale harzburgite intervals from the Open Pit

Yudovskaya et al. 2015 – J. Pet.

Uitkomst Intrusion – South Africa

- ❖ Contained a total measured and indicated resource of 6.23 Mt. of chromite ore with a grade of 33.47% Cr2O3 that is now largely mined out
- ❖ One of the most complete profiles, intersecting the entire ~850 m of intrusive stratigraphy and significant segments of its hanging wall and footwall rocks, is provided by drill core (SH 176)





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Maier et al. 2018 – Mineral Deposita

Uitkomst Intrusion

Different textural relationships between chromitite and harzburgite in the borehole cores…

(a) Rounded chromitite fragments (oulined in red) immediately above the top of the chromite seam (LM6-738)

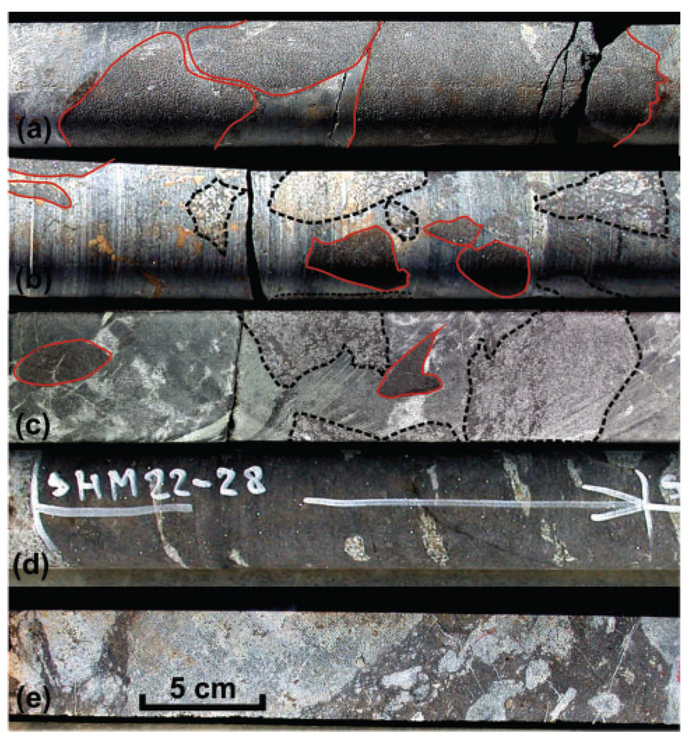
(b) Angular fragments of chromitite (red lines) and serpentinized chromitiferous harzburgite (dashed lines) in Cr-poor harzburgite (LM6-739)

(c) Same interval with chromitite and harzburgite clasts as in (b) in half-cut core (LM6-739)

(d) Oriented arrangement of harzburgitic relics in massive chromitite (SHM022-341.5)

(e) Chaotic angular and rounded clasts of harzburgite in chromitite matrix

Yudovskaya et al. 2015 – J. Pet.



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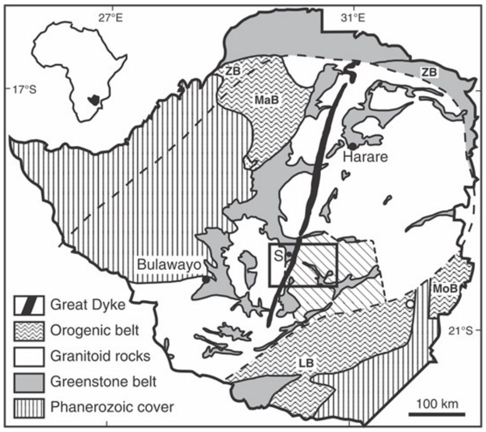
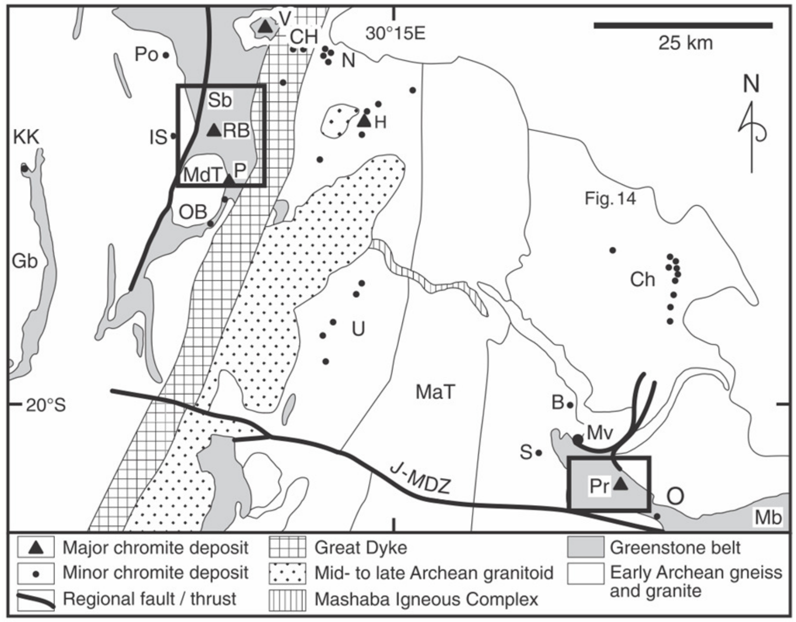
Zimbabwe Craton - Zimbabwe

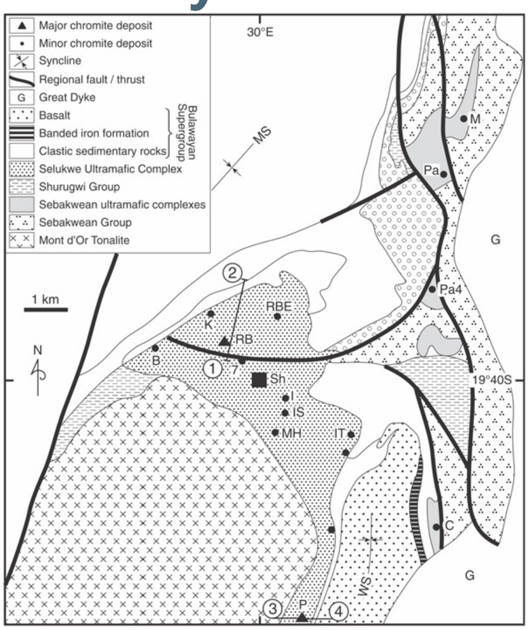


Archean Komatiitic Sill-Hosted Chromite Deposits



Prendergast 2008 – Econ Geol

Railway Block – Shurugwi Greenstone Belt



Major & minor chromite deposits

- **RB = Railway Block**
- P = Peak
- B = Barbados
- K = Kinraids
- RBE = Railway Block East/Golf Course
- 7 = 7 area
- I = Ironsides
- IS = Ironsides South
- MH = Magazine Hill
- IT = Iron Ton
- M = Mount
- Pa = Parefin
- Pa4 = Parefin 4
- C = Cissy

Bulk compositions & total mine outputs from komatiitic sill-hosted Deposits – Railway Block

Mine-deposit	Cr_2O_3 (wt %)	FeO (wt %)	SiO_2 (wt %)	Al_2O_3 (wt %)	MgO (wt %)	Cr/Fe	000t Output
			Greenschist-hosted				
Railway Block							8757
1 Body, levels 174-330	46.93	12.26	7.7	12.3	15.7	3.37	
2 Body, 210-270	47.38	11.93	7.1	12.3	15.8	3.5	
4 Body, 300-360	44.56	13.22	10.22	14.47	13.63	2.97	
7 Body (Priority)							
levels 330-360	44.56	12.41	10.73	11.71	16.29	3.16	
420-480	43.67	11.77	10.04	11.33	15.43	3.27	
480-540	40.55	11.13	14.96	11.22	14.15	3.21	
540-600	36.89	11.58	19.13	11.06	12.58	2.8	
600-660	35.82	11.99	18.41	11.73	14.29	2.63	
660-720	35.77	13.06	15.65	10.35	14.86	2.41	

Prendergast 2008 – Econ Geol

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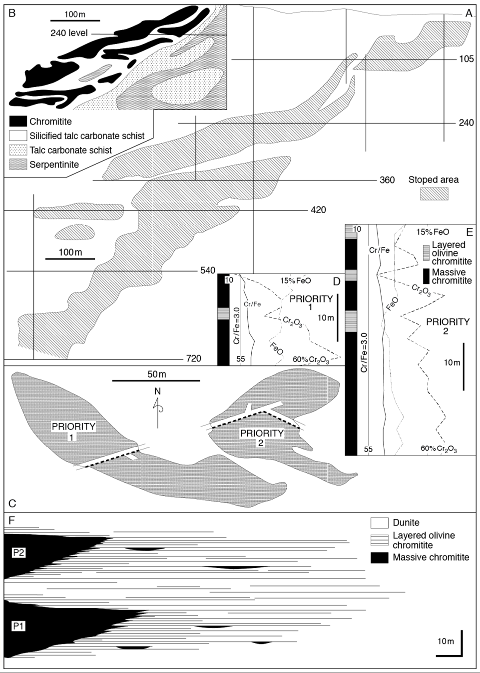
Railway Block – Shurugwi Greenstone Belt



- 500 – 800 m thick sequence
- Sheared and metasomatised serptentinites
- Chromitite bodies situated in silicified talc-carbonate unit
- Divided into Priority 1 and 2, ~137 m wide and ~9 m thick
- "Priority bodies" – Dunites, layered olivine-chromitite, and small massive chromitites
  - Formed primary, elongate shape bodies that grades from massive to layered olivine-chromitite
  - Formed within long-lived channels that developed by focused magma across the floor of the magma chamber between active parts of inflow and outflow feeder dikes

Prendergast 2008 – Econ Geol

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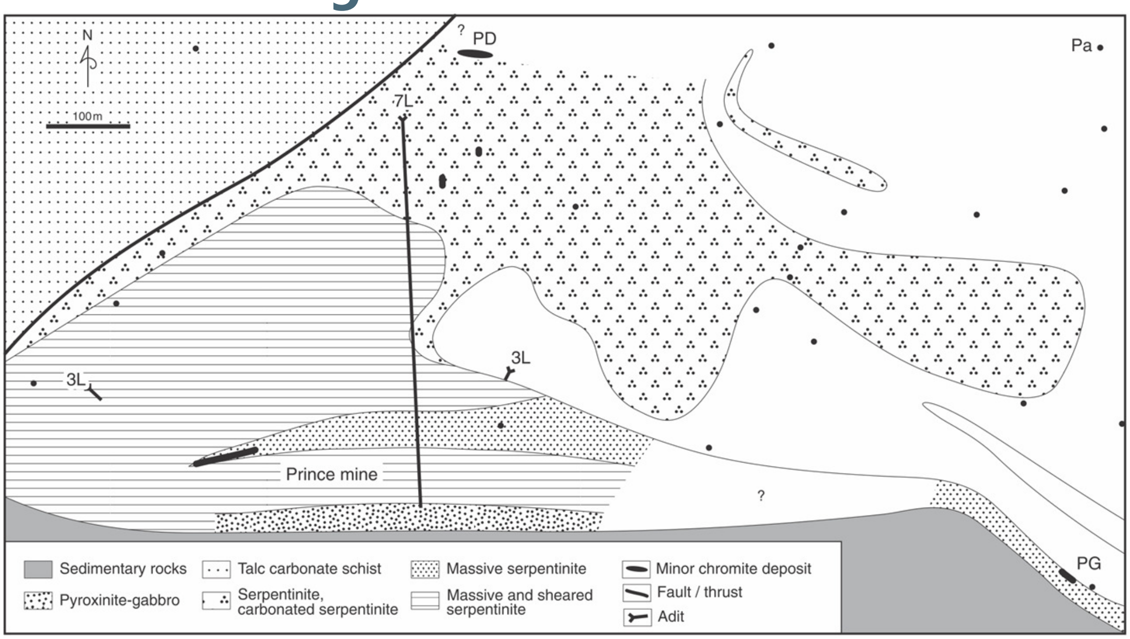
Prince – Masvingo Greenstone Belt



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Prendergast 2008 – Econ Geol

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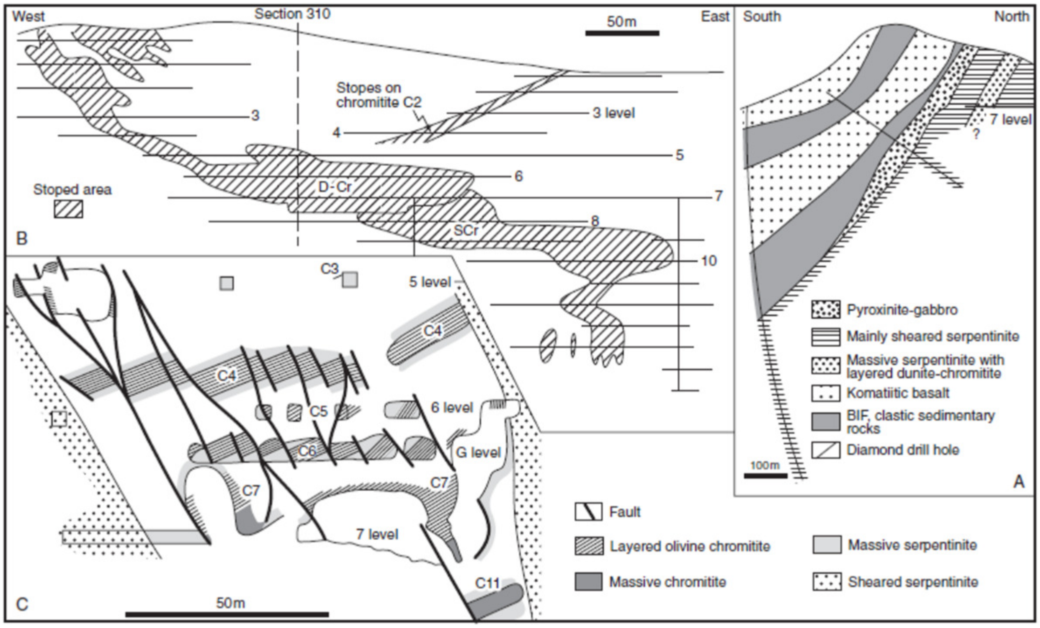
Prince – Masvingo Greenstone Belt



Prendergast 2008 – Econ Geol

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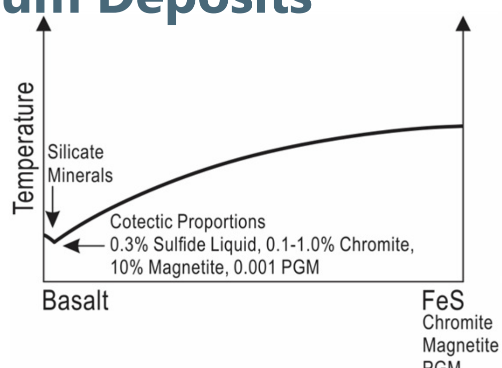
Ore-Forming Processes – Chromium Deposits

- Typical concentration of Cr and V in basic and ultrabasic magmas are 200 to 1,000 ppm whereas current mining activities exploit orebodies that grades 25 to 35 wt.% Cr (36.5 to 51.5 wt.% Cr_2O_3) and 0.1 to 1 wt.% V (0.2 to 1.8 wt.% V_2O_5)
  - Thus enrichment factors to produces an ore bodies is order of magnitude higher



- Normal close-system fractional crystallization of magma is unlikely to produce significant enrichment of ore minerals
- Schematic binary phase diagram illustrate the proportions of chromite and magnetite that form at the cotectic point
  - For chromite btw 0.05 to 0.5% (Irvine 1975, Muck & Campbell 1986, Barnes 1986); up to 1% chromite
  - For magnetite btw 8 to 13% (Toplis & Caroll 1995); up to 10% magnetite

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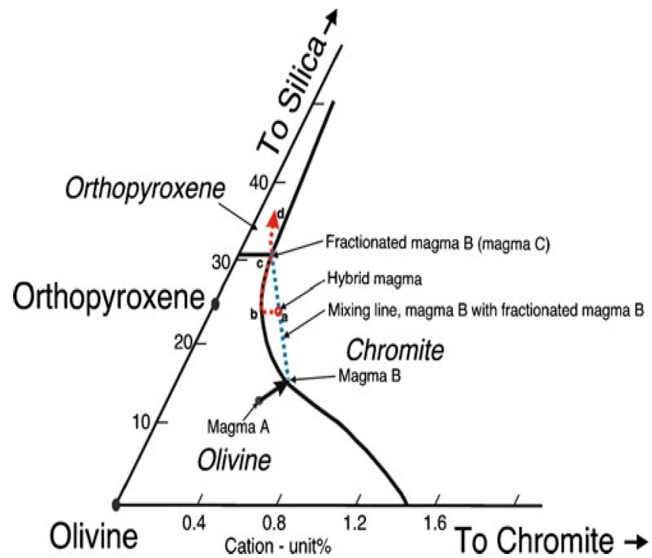
Ore-Forming Processes – Chromium Deposits

- Normally chromite is expected to crystallize with olivine along the cotectic line (solid black line).
- Compositional changes is need it, so the system ONLY crystallizes chromite for some time in order to generate massive chromite layers…
- Chromite crystallization WITHOUT simultaneous olivine crystallization requires chemical disequilibrium and change in bulk composition



Naldrett et al. 2012 – Mineral Deposita

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Ore-Forming Processes – Chromium Deposits

Fundamental in the genesis of all chromite deposits is how layers of massive to semi-massive chromite could be generated?

- ***Mass-balance problem:***
  - Campbell and Murck (1993) made some basic calculation for the genesis of the G & H Chromitites in the Stillwater Complex, such one-dimensional modeling is too simplistic but illustrates the problem.
  - A typical chromitite layer may have 45 wt.% Cr_2O_3 (300,000 ppm Cr) and assuming that 200 ppm Cr could be extracted from magma of density 2.7 g/cm^3 () to crystallize chromite with a density of 4.5 g/cm^3, a 1-m-thick layer of chromitite would have required processing a 2.5-km-thick magma column
  - Thick chromitite layers in Stratiform magmatic conduit type deposits exacerbate this mass-balance problem
    - Ipueira-Medrado: 5-8 m-thick chromitites
    - Inyala-Rhonda: 10s m-thick chromitites
    - Sukinda: 3-4 m-thick chromitites
    - Uitkomst: up to 6 m-thick chromitites
    - Peak-Railway Block: 10s m-thick chromitites
    - Kemi: 20 (up to 90) m-thick chromitites
    - ***Black Thor: up to 100 m-thick chromitites***

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Ore-Forming Processes – Stratiform Deposits

Many processes have been proposed to account for this enrichment, all have inherent issues, merits and weakness…All these processes are not mutually exclusive!

In-Situ Crystallization Models

- Crystal sinking and sorting *(e.g. Jackson 1961)*
- Liquid immiscibility *(e.g. McDonald 1965)*
- Oxidation *(e.g. Ulmer 1969, Ferreira-Filho & Araujo 2009)*
- Crustal contamination *(e.g. Irvine 1975 - Si, Spandler et al. 2005, Rollinson 1997 - BIF)*
- Variations in fO_2 and total pressure *(e.g. Cameron 1980, Lipin 1993, Latypov et al. 2017)*
- Magma mixing *(e.g. Irvine 1977, Campbell & Murck 1993)*
- Hydration *(Prendergast 2008, Azar 2010)*
- Dynamic crystallization *(Yudovskaya et al. 2015)*
- Cumulate melt interaction (Arai & Abe 1995, Bédard & Hébert 1998,O'Driscoll et al. 2010)

Physical Transport Models

- Injection of chromite-phyric magma (i.e., magma slurries) *(Eales 2000, Mondal & Mathez 2007 Voordouw et al. 2009)*
- Magmatic slumping *(e.g., Maier et al. 2013, Fioren 2015)*

In-Situ Crystallization & Physical Transport Models

- Dynamic upgrading of Fe ± Ti oxide xenocrysts *(Lesher et al. 2019)*

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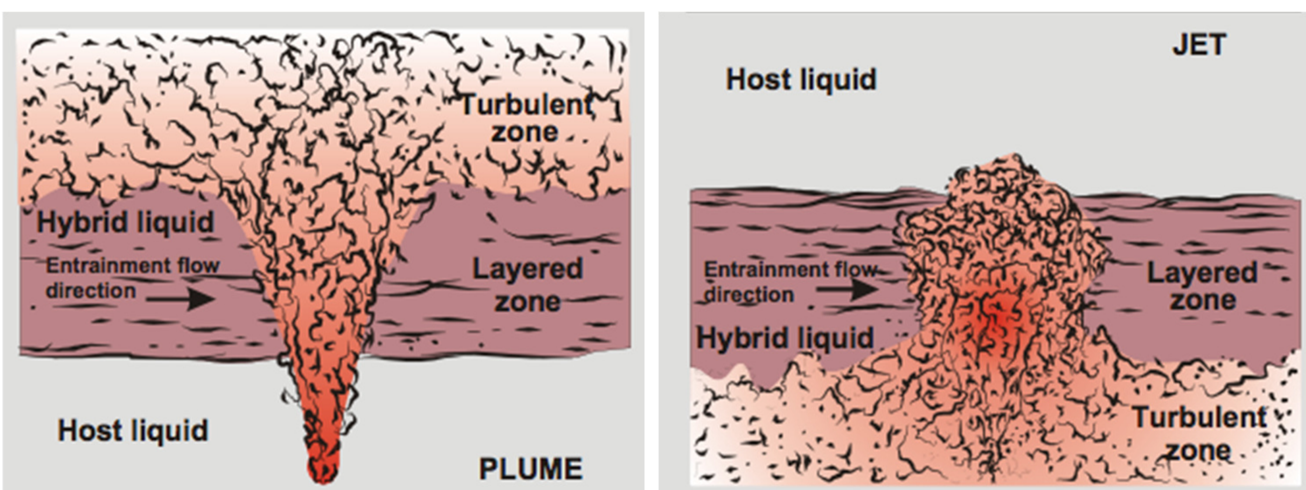
Magma Mixing



May be enhanced by turbulent mixing of fractionated resident magma and new magma in a plume or in a jet

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Campbell & Turner 1985 – J. Pet

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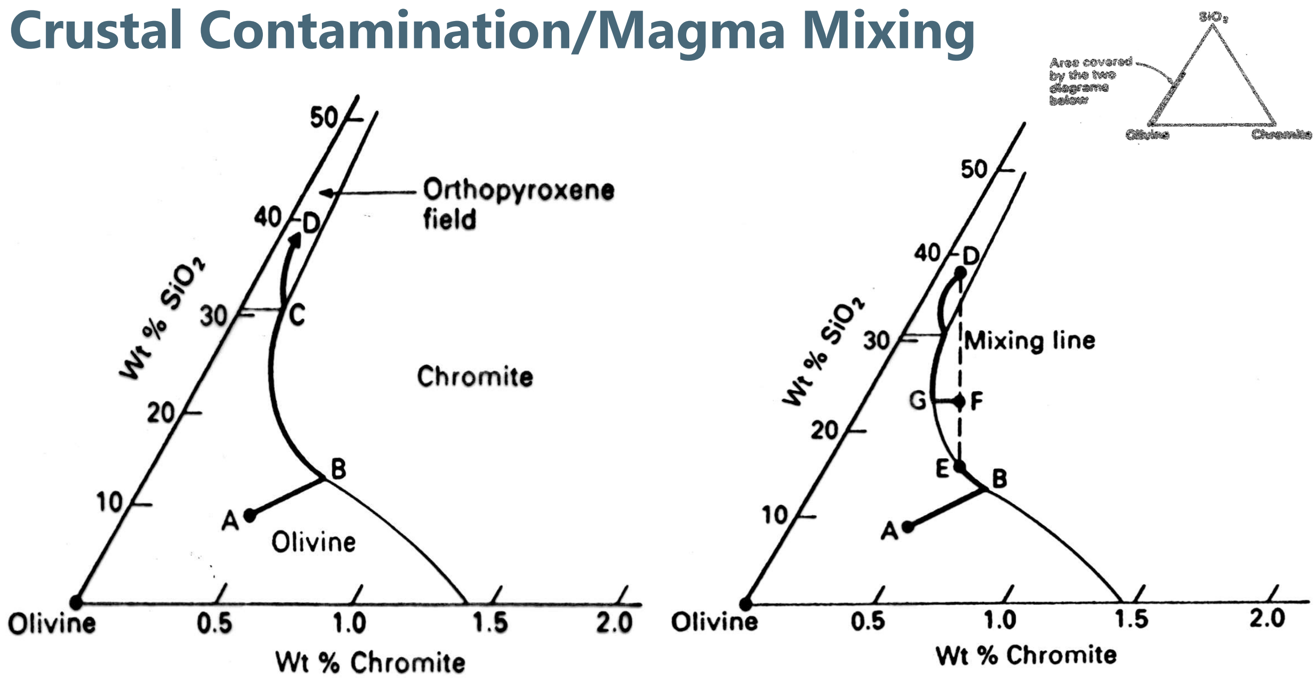
Crustal Contamination/Magma Mixing



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Irvine 1975, 1977 – Geology

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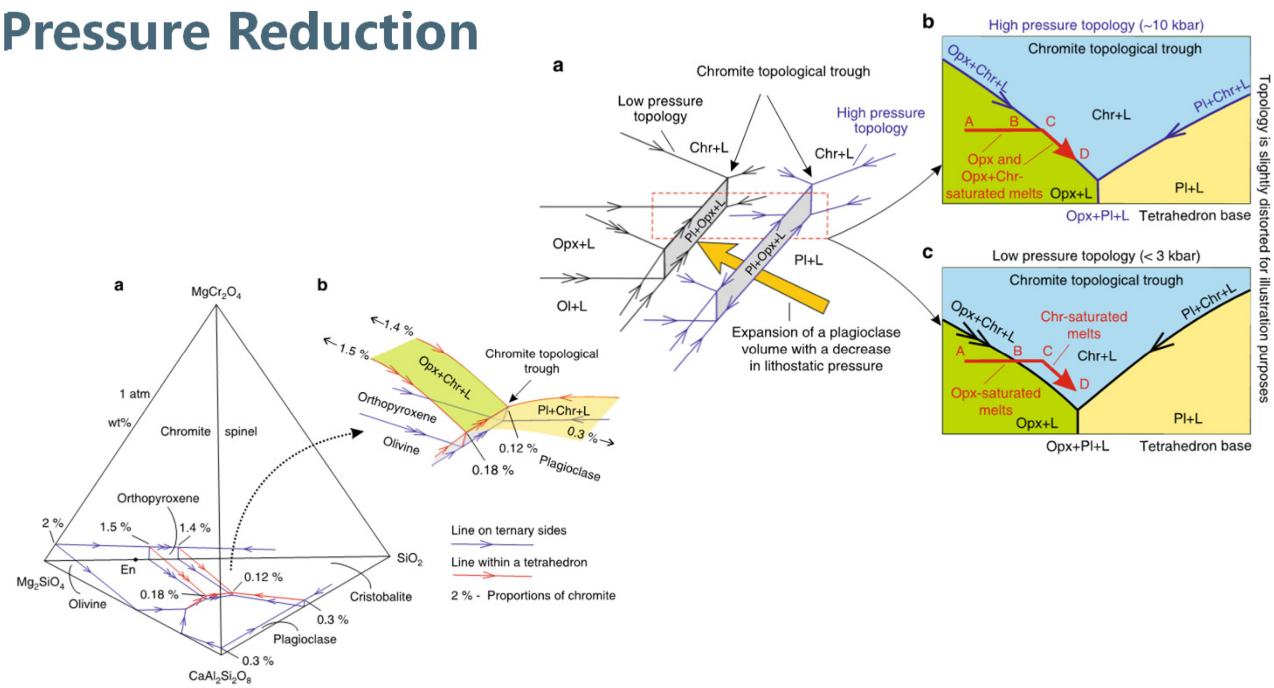
Pressure Reduction



Lapytov et al. 2017 – Nature

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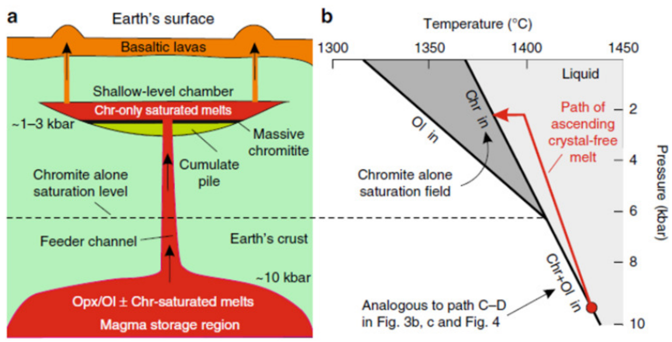
Pressure Reduction

a) A physical model for the generation of basaltic melts saturated in chromite alone by a reduction in lithostatic pressure. a Mantle-derived basaltic melts ascending from lower crustal storage regions, or a mantle source, inevitably experience a reduction in lithostatic pressure. This results in shifting of the chromite topological trough and, as a result, basaltic melts located alongside the chromite topological trough, at high pressure regions will become saturated in chromite alone during ascent to shallow-level chambers. Fractional crystallisation of a large volume of these chromite-saturated melts, in an open system where magma can also flow out of the chamber, will produce monomineralic layers of massive chromitites in mafic-ultramafic intrusions.

b) Phase relations for a primitive basalt (MgO = 15.13 wt.%; Cr2O3 = 0.10 wt.%) in P–T space illustrating the model that basaltic melts located alongside the chromite topological trough first become slightly superheated during their ascent and then saturated in chromite alone after stalling and cooling in shallowlevel chambers.

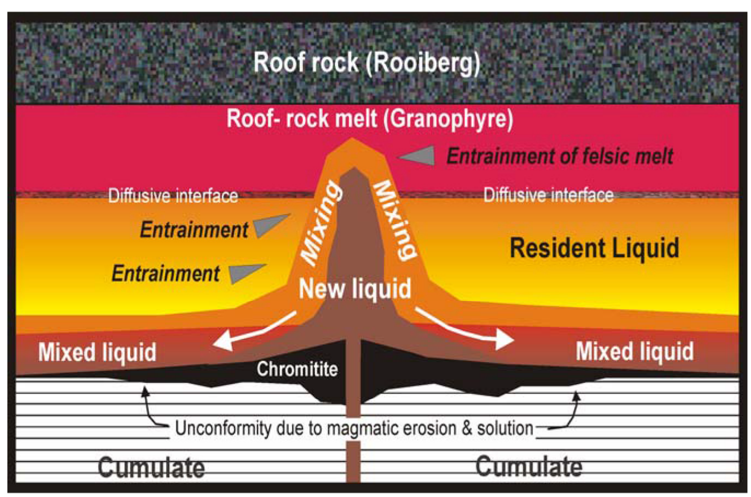
Therefore, allowing for the development of massive chromitites in shallow-level chambers. This case is analogous to path C–D in Fig. 3b, c and Fig. 4c, in which multiply-saturated liquids become saturated in chromite alone with pressure reduction. The phase diagram is simplified from Fig. 10 in ref. 28 and is only used to graphically illustrate the principle lying at the heart of our model



Lapytov et al. 2017 – Nature

Magma Mixing / Crustal Contamination

Schematic diagram of the envisaged magma intrusion and mixing process. Introduction of a new magma (Ro = 0.705 – 0.706) as an active fountain resulted in entrainment of resident mafic liquid and if there was sufficient upward momentum, roof-rock melt (Ro >0.72) was also entrained. This resulted in contamination by a silica-rich component with the resulting forced crystallization of chromite and PGM. The mixed liquids were out of equilibrium with the floor cumulates and so reacted and eroded to form an unconformity on to which the chromite–PGM ore was deposited sulfides



Kinnaird et al. 2002 – TransIMM

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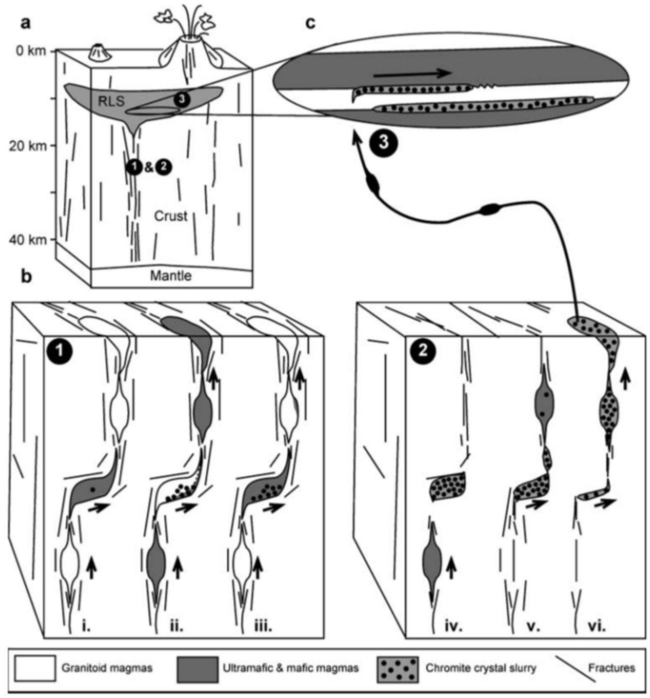
Intrusive - Slurries

1. *Accumulation of chromite crystal slurry in a structural trap*
   i: Cr-saturated mafic melt in structural trap
   ii: precipitation and accumulation of Chr through mixing with felsic melt
   iii: replenishment of Cr-saturated mafic melt to start next cycle of chromite accumulation
2. *Mobilization of chromite crystal slurries*
   iv: chromite accumulation residing in structural trap
   v: by-passing of silicate melt that triggers the ascent of chromite crystal slurry
   vi: ascent of chromite crystal slurry
3. *Emplacement of chromite crystal slurries along lithological contacts in the Rustenburg Layered Suite*



Voordouw et al. 2013 – Min Pet

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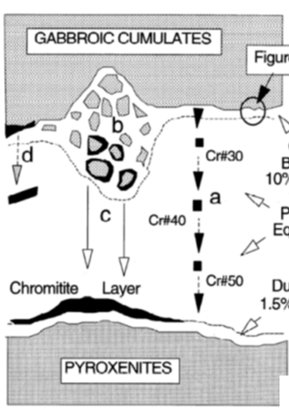
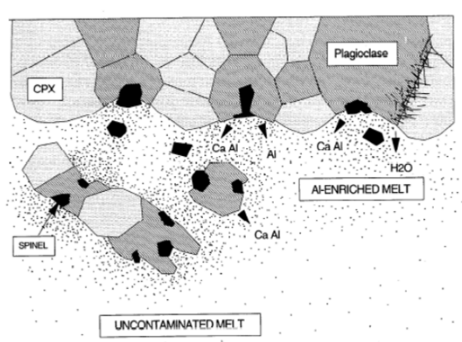
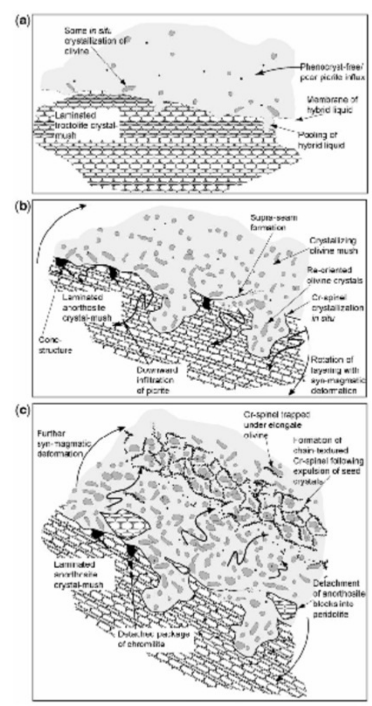
Cumulate-Melt Interaction

The main Cr-spinel seams crystallized in situ, and are a crystallization product of assimilation of plagioclase-rich cumulate by a picritic melt. Coeval syn-magmatic deformation of the cumulate mush drove Cr-spinel crystals several centimetres upwards, during intercumulus liquid expulsion, giving rise to the supra-seams and chain-textured peridotite immediately above the unit boundaries.





Bédard & Hébert 1998 – JGR



O'Driscoll et al. 2010 – J Pet

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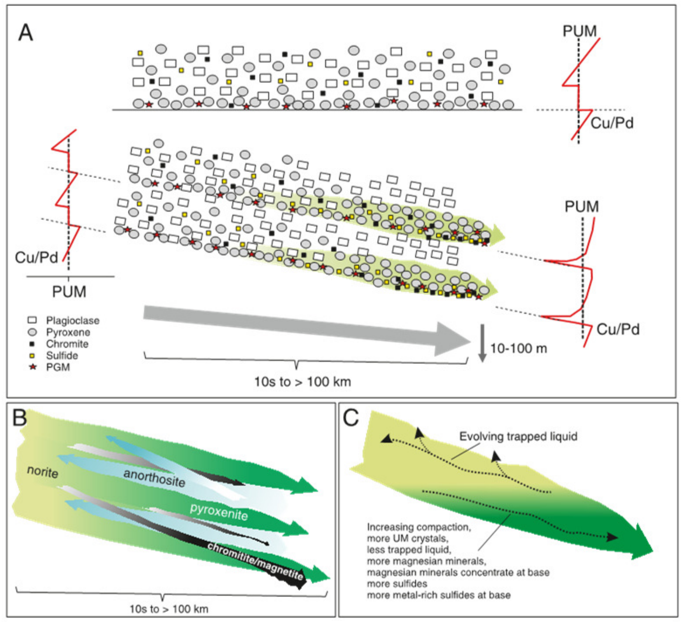
Magmatic slumping

A) *Semi-consolidated proto cumulate deposited by fresh influx of sulfide-undersaturated magma, precipitating Pyx-Chr-PGM and later Plag-Sul; cumulate layers density sorted during down-dip slumping.*

B) *Relative movements of pyroxenite and oxide vs feldspathic slurries.*

C) *Compositional evolution of slurries during slumping, including relative con-centration of mafic minerals and sulfides towards the base of slurry and centre of intrusion and percolation of metal-depleted inter-cumulus residual liquids upward across slurries and up-dip towards intrusion margin, leading to progressive lowering of metal tenors of intercumulus sulfides*



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Maier et al. 2013 – Mineral Deposita

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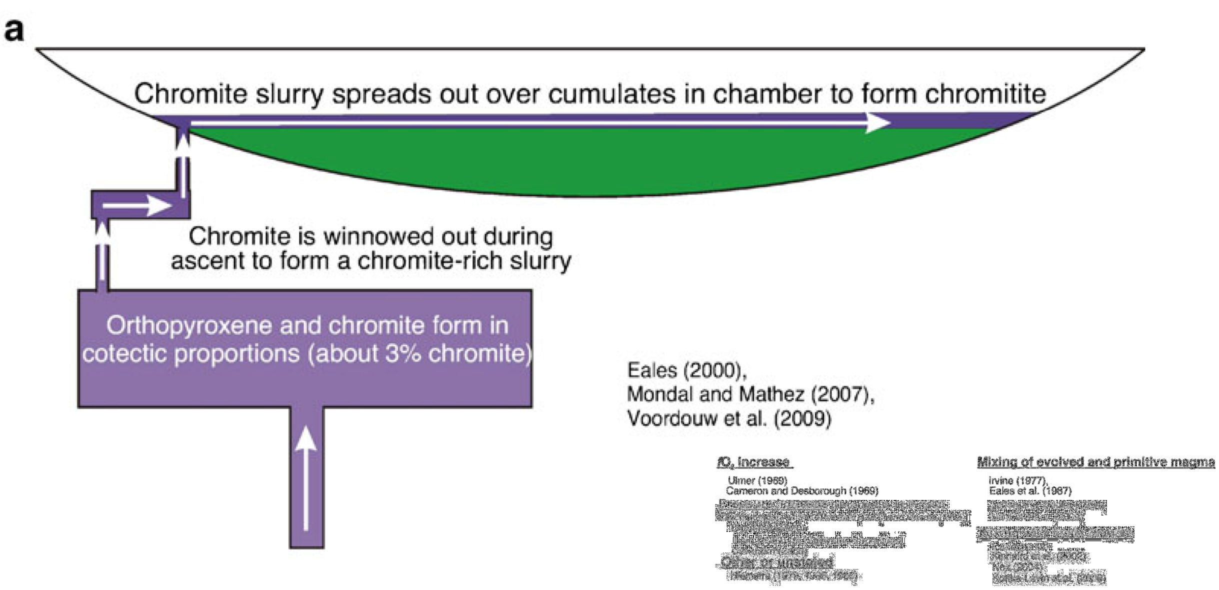
Off-Stage



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Naldrett et al. 2012 – Mineral Deposita

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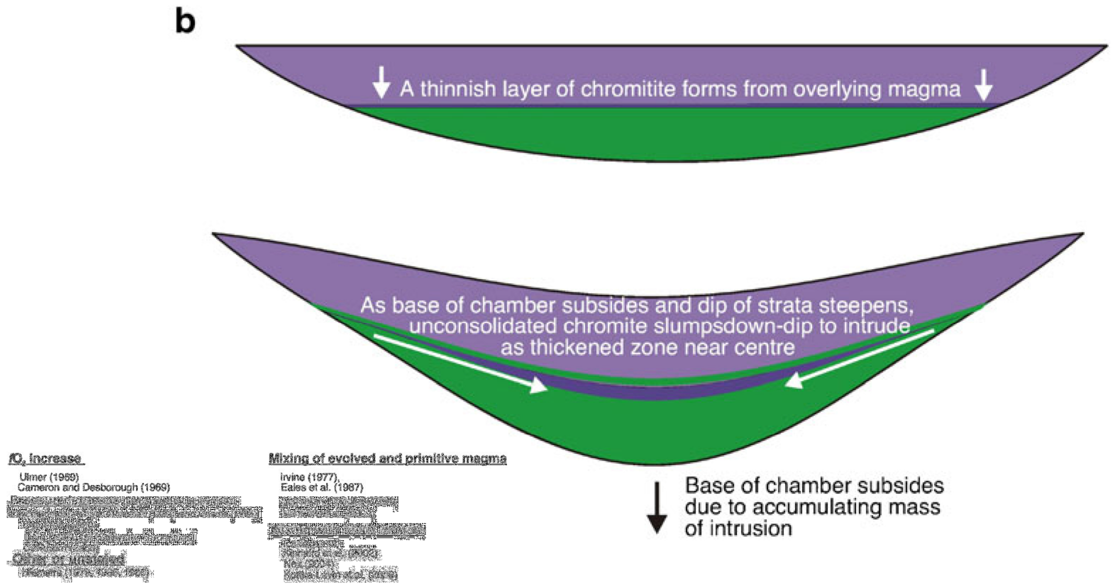
Off-Stage



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Naldrett et al. 2012 – Mineral Deposita Canada

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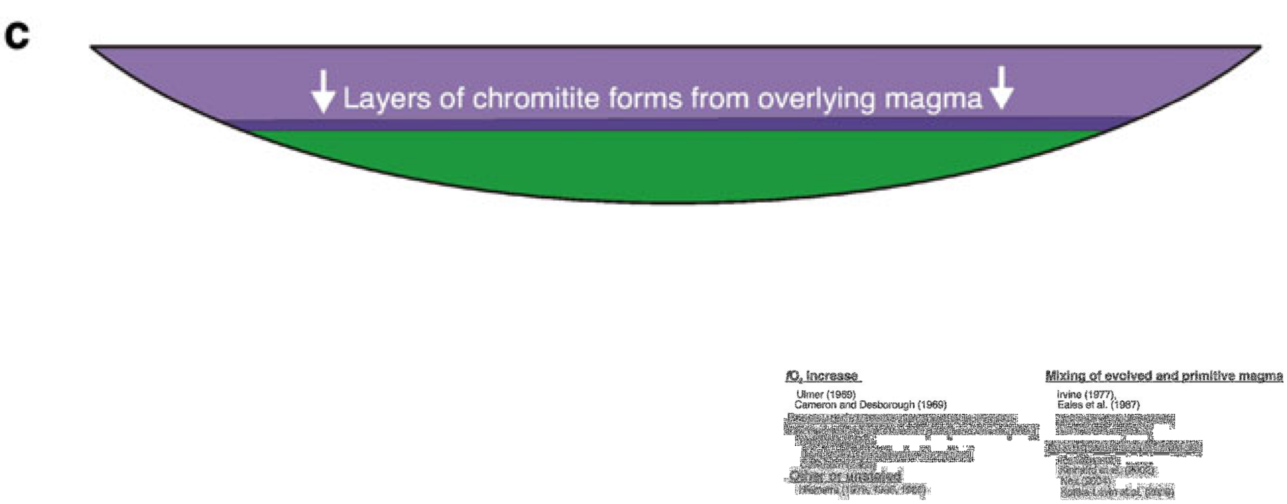
On-Stage



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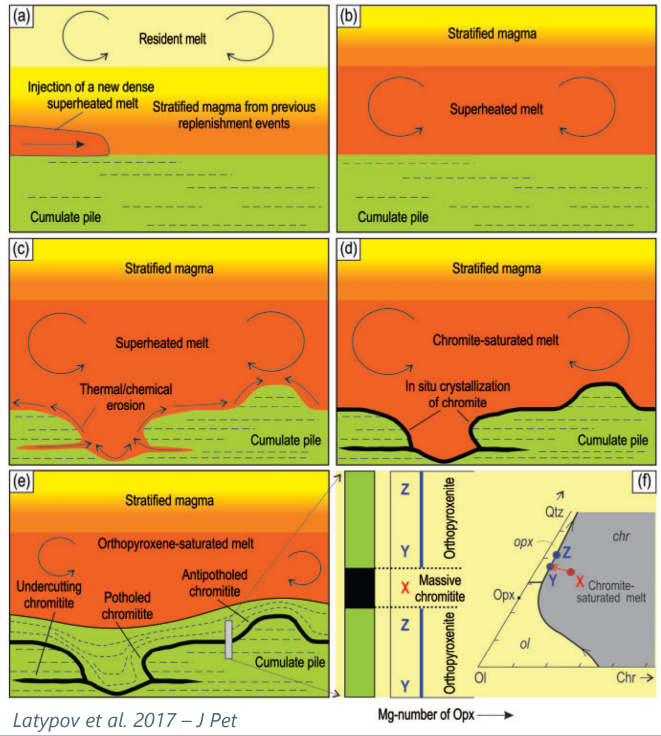
Naldrett et al. 2012 – Mineral Deposita Canada

Magma Mixing

Origin of the Bushveld chromitites by in situ crystallization from a basal layer of chromite-saturated melt. There is a basal layer of vertically stratified magma produced by previous events of magma chamber replenishment.



Latypov et al. 2017 – J Pet

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At the base the magma crystallized chromite-bearing orthopyroxenite [along a path Y–Z in (f)]. Then at some point (a, b), a dense, primitive and superheated magma entered the chamber and spread across the floor of the chamber as a basal layer beneath a column of stratified magma. The superheated magma caused thermochemical erosion of cumulates at the temporary floor of the chamber (c), developing potholes and antipotholes with associated sheet-like cavities within the footwall rocks (shown out of scale). On cooling, the magma crystallized chromite (6 sulphide) [along a path X–Y in (f)] on the irregular erosional surface (d), developing normal, potholed and overturned chromites, as a first chromitite sublayer. Chromite and droplets of sulphide melt scavenged PGE from a large volume of magma that was continuously brought to the crystal–liquid interface by convecting magma. This allows the chromite and sulphide melts to equilibrate with a large volume of basaltic magma. Repetition of this sequence of events resulted in the formation of several sublayers of chromitite that collectively appear to be a single thick layer of chromitite, with or without thin partings of silicate rocks. Slight fluctuations in the composition of the inflowing magma during these events gave rise to texturally and compositionally different sublayers. At some point (e) the chamber was replenished by pulses of orthopyroxene-saturated magma that were not in thermal/chemical equilibrium with the chromite cumulates. This resulted in the termination of chromite crystallization and the partial erosion of chromitites followed by crystallization of orthopyroxene [again along a path Y–Z in (f)]. It should be noted that cryptic variations in the orthopyroxenites above and below chromitite are lacking because they crystallize from compositionally similar magmas evolving along the same path Y–Z in (f).

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Latypov et al. 2017 – J Pet

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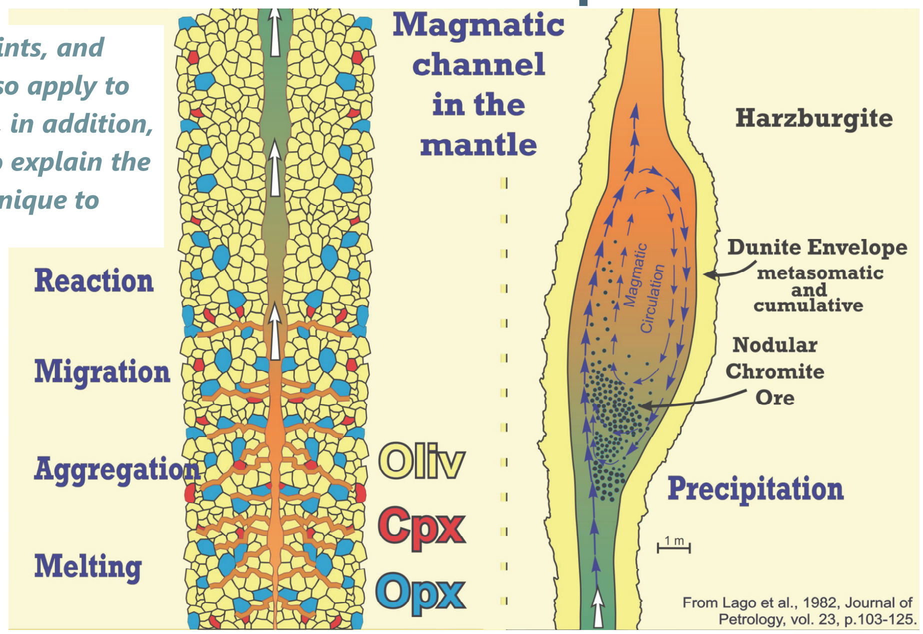
Ore-Forming Processes – Podiform Deposits

Many of the issues, constraints, and hypotheses debated above also apply to podiform chromitites. However, in addition, any successful model must also explain the origin of the ore textures unique to podiform deposits

Some authors have attributed the origin of the nodules to mechanical processes, such as chromite aggregation ("snowballing") in convecting magma conduits or break-up of semi-plastic chromitite stringers. Both these processes should be capable of occurring in stratiform chromitite ores but have never been recorded therein.



From Lago et al., 1982, Journal of Petrology, vol. 23, p.103-125.

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Pagé 2014 – MERC Workshop

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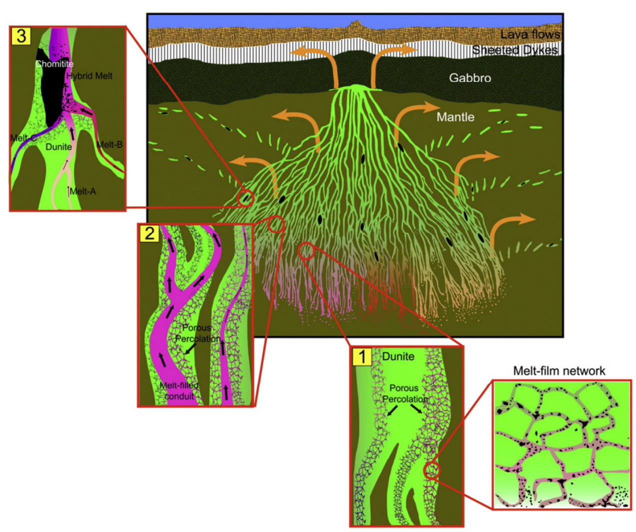
Ore-Forming Processes – Podiform Deposits

A network of dunite channels drains melts ascending from different sources (marked with different colours) in the heterogeneous deeper mantle

(1) Ascending melts move mainly by porous percolation through a melt-film network; in the zone of intersection between dunite channels mixing of basaltic melts with different SiO_2 promotes precipitation of chromite. The image is not to scale, as grains of olivine are generally from <0.5 mm to a few centimeters.

(2) Focused flow of melt produces melt-filled channels in dunite allowing the chemical isolation and rapid ascent of the melts

(3) Chemically isolated melts drained through different channels in the dunite meet and mix to produce hybrid melts able to precipitate volumes of chromitite. The size of the dunite network and the chromitite bodies can vary from a few metres to many kilometers.



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From González-Jiménez et al. 2014 - Lithos

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Still a Fundamental Problem?

Conduit-hosted chromite deposits contains orders of magnitude more chromite than what is typically be precipitated from a mafic-ultramafic magma, so the key question is **why did so much chromite crystallize ?**

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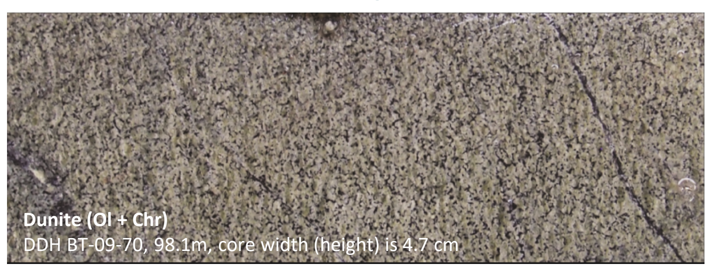

Low-Mg komatiitic magmas are normally saturated in chromite, evident by the presence of olivine + chromite in ≥ cotectic proportions

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Still a Fundamental Problem?

	Chromitite Thickness (m)	Host Unit (m)	Parental Magma	OXIF Country Rocks	Xenoliths
Black Thor – Blackbird	up to 100	1500	low-Mg komatiite	yes	BIF, gabbro
Inlaya – Rhonda	10s	100s	komatiitic	yes	none reported
Ipueira-Medrado	5-8	300	basaltic	none reported	none reported
Kemi	0.5-90, ave 20	up to 2000	basaltic	none reported	none reported
Peak – Railway Block	10s	100s	komatiitic	yes	basalt, BIF
Sukinda	3-4	up to 400	SHMB	yes	none reported
Uitkomst	up to 6	~800	high-Mg basalt	yes	dolomite, Mag-shale

OXIF – oxide-facies iron formation. **SHMB** – siliceous high-magnesian basalt. References in text.

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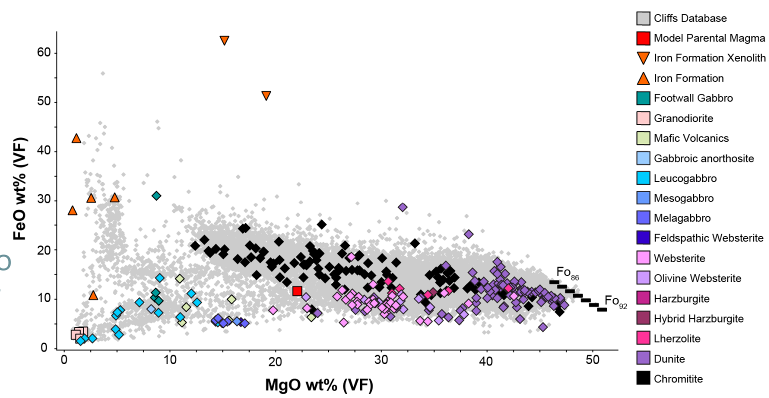
Dynamic Upgrading Model - Wholesale IF Assimilation

Wholesale **assimilation of IF has several problems (e.g., Rollinson 1997):**

- Most mafic-ultramafic magmas (including BTI, which contains cotectic Ol-Chr cumulates beneath the chromitites) are saturated in chromite, so would not be able to assimilate much (if any) magnetite



- Adding an assimilant containing >20% FeOt to a komatiitic magma would significantly increase the Fe/Mg ratios of Ol, Opx, and Cpx, which is not observed (left): Cr-poor BTIC rocks have normal Fe contents
- MELTS models (e.g., Azar 2010 MSc) indicate that the amount of chromite generated by this process is less than 0.3%, not nearly enough

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Dynamic Upgrading Model - Partial Assimilation of IF

Partial assimilation of iron formation would involve:

- ❖ Complete dissolution of chert/quartz and Fe-silicates, which would explain the high abundance of Opx in komatiitic magmas that do not normally crystallize much Opx.
- ❖ Magnetite would not dissolve (because the magma is saturated in chromite), but could be upgraded to chromite via equilibration with abundant Cr-rich magma (i.e., diffusions with a high effective R factor).
- ❖ Not dissolving magnetite would not change the Fe content of the magma significantly, accounting for the lack of observed Fe enrichment in the BTIC.
- ❖ The iron formation near the BTI (e.g., FN-09-01) is composed of magnetite + quartz + actinolite ± sulfides.

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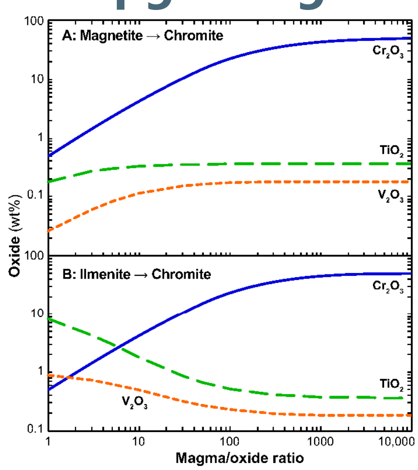
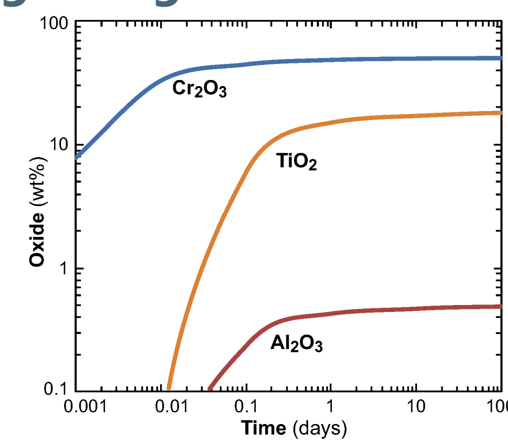
Dynamic Upgrading Model - Upgrading



Using conservative abundances of Cr in the magma and reasonable partition coefficients for Cr and Ti, the results indicate that magma/oxide ratios as low as 100 can produce Cr-rich chromites.



Calculated abundances of Cr-Al-Ti diffused into core of 0.1-mm-diameter magnetite grain. The results indicate that 0.1 mm magnetite or ilmenite grains could be completely converted to chromite in 1–10 days

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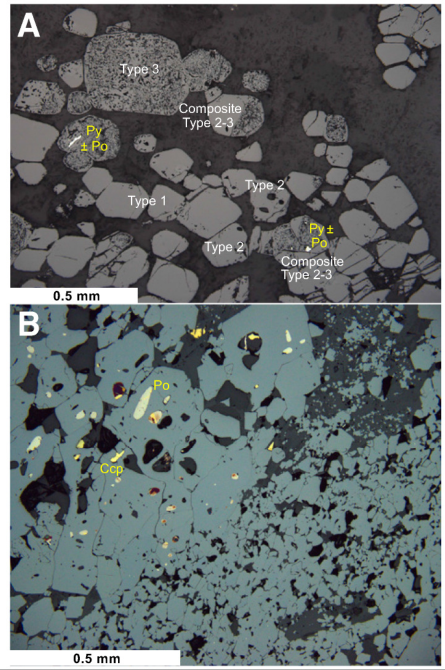
Dynamic Upgrading Model - Xenocrysts

The chromites in the Black Thor intrusion exhibit a wide range of textures including

(1) Massive chromite

(2) Inclusion-bearing chromite (predominantly serpentine-actinolite-chlorite interpreted to represent altered komatiitic melt inclusions)

(3) Pitted chromite with fine Fe ± Cu sulfides. The first and third are similar to the textures of magnetite-silicate±sulfide iron-formations below the Black Thor intrusion, consistent with them being the source of the oxide in this deposit



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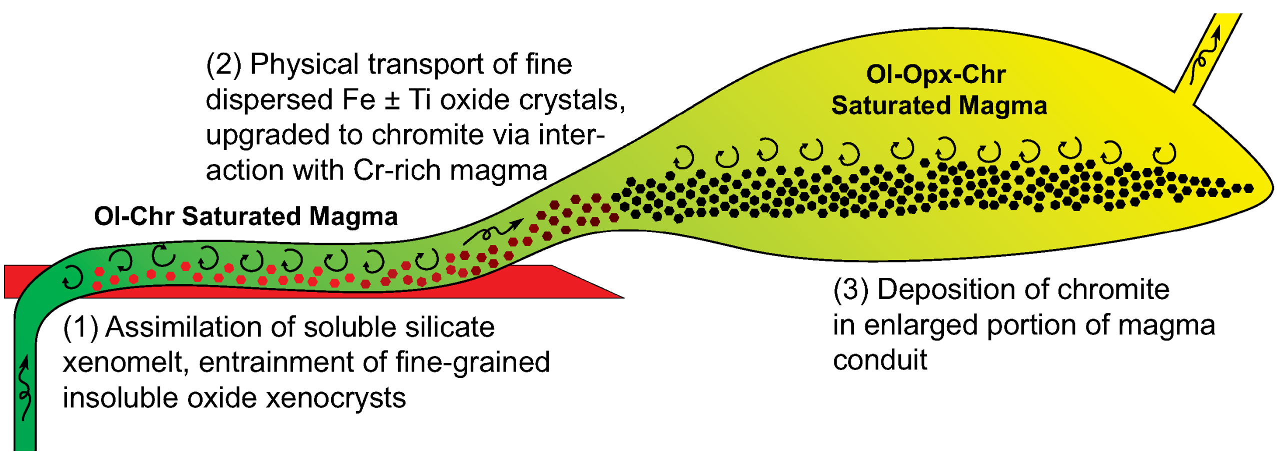
Dynamic upgrading of Fe ± Ti oxide xenocrysts



Model for dynamic upgrading of Fe ± Ti oxides derived from oxide-facies iron formation or ferrogabbro via interaction with Cr-rich komatiitic magma

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Summary – Chromite Deposits

Type	I: Stratiform		II: Podiform
Subtype	A: Layered Intrusion-Hosted	B: Magmatic Conduit-Hosted	
System	Periodically-replenished magma chambers	Continuously-replenished magma conduits	Tectonized upper mantle
Age	Post-Archean	Archean	Phanerozoic-Mesozoic
Setting	Intracratonic	Intracratonic	Ophiolites
Magma	Siliceous high-Mg basalt	Low-Mg komatiitic	Basaltic
Intrusion Size	Very large	Small(ish)	Large
Host Rocks	Peridotite, pyroxenite, gabbro, anorthosite	Dunite, peridotite, pyroxenite, gabbro, anorthosite	Tectonized/serpentinized dunite, harzburgite, wehrlite
Form	Laterally-extensive layers	Laterally-extensive layers and lenses	Discontinuous pods, layers, veins, and schlieren
Textures	Disseminated, patchy, net, semi-massive, massive	Disseminated, patchy, net, semi-massive, massive	Disseminated, semi-massive, nodular
Thickness	Up to 5 m	Up to 100 m	Variable
Ore Location	Layers at mafic/ultramafic transition	Varies, but normally within ultramafic portion of intrusion	Upper mantle section of complex
Ore-Forming Processes	Magma mixing ± contamination and/or physical transport	Magma mixing ± contamination ± oxidation and/or physical transport	Fractional crystallization and/or magma mixing
Examples*	Bushveld, Great Dyke, Stillwater	Black Thor-Blackbird, Kemi, Inyala, Ipueira-Medrado, Sukinda-Nuasahi	Cuba, Iran, New Caledonia, Philippines

Concluding Remarks – Chromite Deposits

Magmatic Cr deposits formed throughout geological time

from a range of mantle-derived magma types

In order for an economic Cr deposit to form, several processes must occur:

- *A picritic-komatiitic-boninitic magma must be generated by moderate to high degree partial melting of the mantle*
- *The magma must be brought to upper crustal levels without reaching chromite saturation*
- *Magma must mix with other magmas or rocks or become contaminated in a way so as to precipitate much greater amounts of chromite than normal or interact with magnetite enough to upgrade it to chromite*
- *The chromite must be segregated and concentrated in a form that is suitable for mining (and preserved from erosion and weathering)*