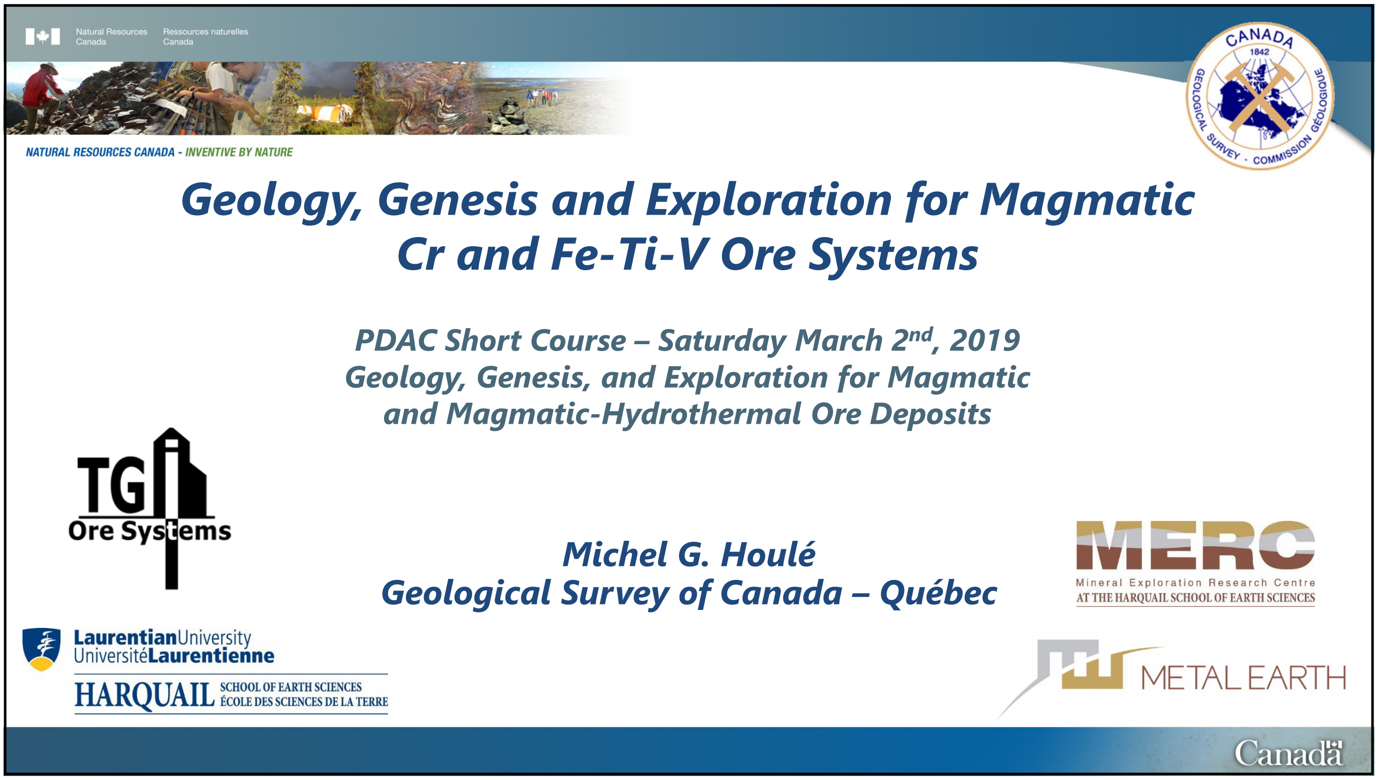
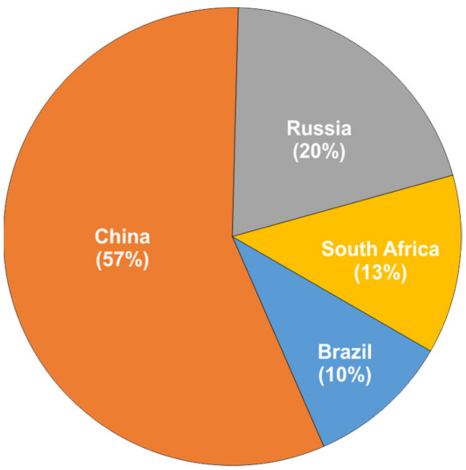

Natural Resources Canada
Ressources naturelles Canada
NATURAL RESOURCES CANADA - INVENTIVE BY NATURE
CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE
Geology, Genesis and Exploration for Magmatic
Cr and Fe-Ti-V Ore Systems
PDAC Short Course – Saturday March 2nd, 2019
Geology, Genesis, and Exploration for Magmatic
and Magmatic-Hydrothermal Ore Deposits
TGI Ore Systems
Michel G. Houlé
Geological Survey of Canada – Québec
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
METAL EARTH
Canada


Natural Resources Canada
Ressources naturelles Canada
NATURAL RESOURCES CANADA - INVENTIVE BY NATURE
CANADA 1842 GEOLOGICAL SURVEY - COMMISSION GÉOLOGIQUE
Geology, Genesis and Exploration for Magmatic
Fe-Ti-V Ore Systems
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
METAL EARTH
Canada

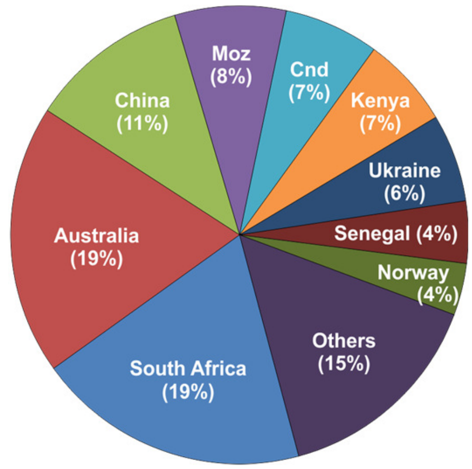
3

World V and Ti Production *in 2016-V / 2017-Ti*

Vanadium Production (2016)



Titanium Production (2017)



Data from the USGS Mineral Resources Program

Natural Resources Canada Ressources naturelles Canada

Canada

4

Uses and Applications

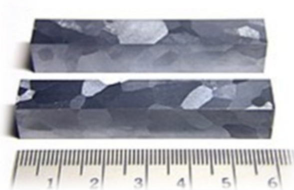
Proprieties

- Vanadium is a medium-hard, ductile, bright steel-blue metal
- Has good resistance to corrosion and it is stable against alkalis and sulfuric and hydrochloric acids

Uses

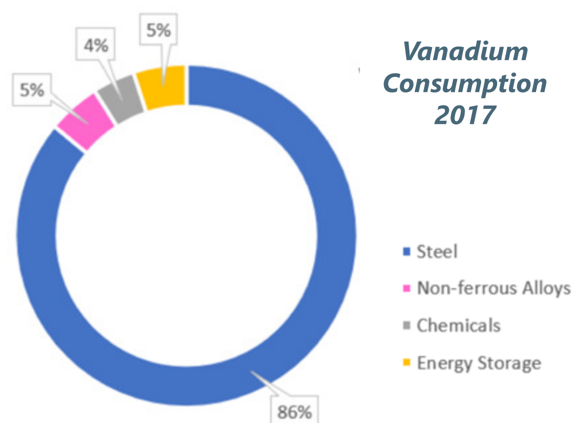
- Most V is used as steel additive (ferrovanadium) steel to make it stronger
- High-strength low-alloy containing V are widely used for auto parts, buildings, bridges, etc.
- Aerospace application: V-Ti alloys have best strength-to-weight ratio
- Is becoming more widely used in green technology (Vanadium Reflux Flow Batteries)

Schulz et al. 2017 – USGS PP1802



High-purity Vanadium (99.95%)

Vanadium Consumption 2017



Source: Vanitec

Natural Resources Canada Ressources naturelles Canada

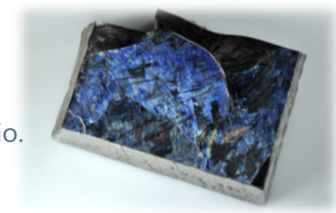
Canada

5

Uses and Applications

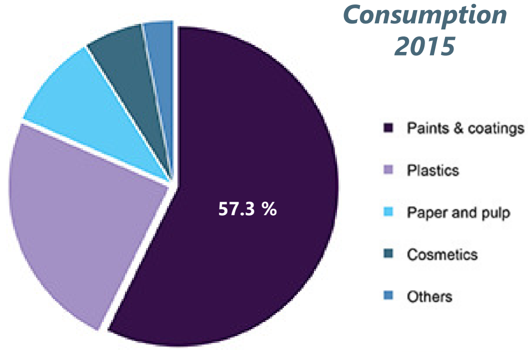
Proprieties

- Titanium is recognized for its high strength-to-weight ratio.
- It is a strong metal with low density that is quite ductile, lustrous, and metallic-white in color
- ***Uses***
- Pigments, additives, and coatings (paints, paper, toothpaste, and plastics)
- Aerospace and marine (as steel additive)
- Industrial (pipe and process equipment such heat exchangers, tanks, etc.)
- Consumer and architectural (automotive applications, sporting goods, etc.)
- Jewelery (Titanium ring, etc.)
- Medical (surgical implements and implants, such as hip balls, joint replacement and dental implants)



High-purity (99.999%) titanium with visible crystallites

Titanium Consumption 2015



Source: Grand View Research

Natural Resources Canada / Ressources naturelles Canada

Canada

6

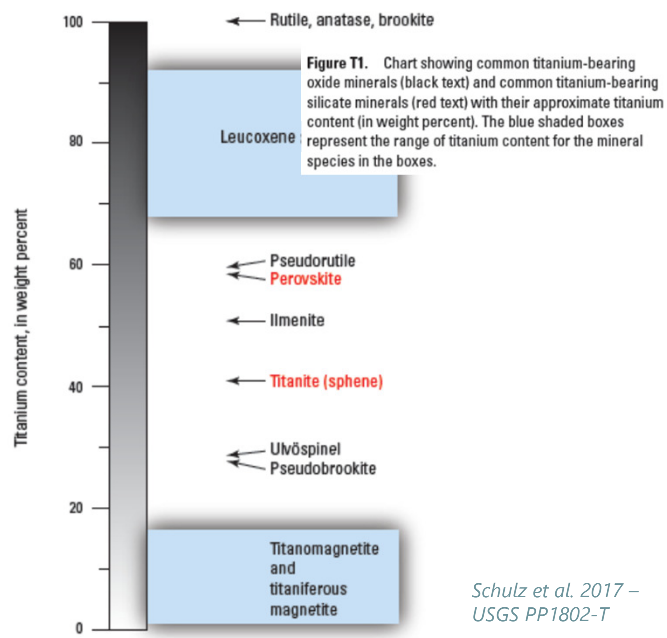
Mineralogy

Vanadium-bearing minerals

- Coulsonite – $Fe^{2+}V^{3+}{}_2O_4$
- Hematite – Fe_2O_3
  - Common impurities: Ti,Al,Mn,H2O
- **Ilmenite – $Fe^{2+}TiO_3$**
  - Common impurities: Mn,Mg,V
- **Magnetite – $Fe^{2+}Fe^{3+}{}_2O_4$**
  - Common impurities: Mg,Zn,Mn,Ni,Cr,Ti,V,Al
- Perovskite – $CaTiO_3$
  - Common impurities: Fe,Nb,Ce,La,TR
- Rutile – TiO_2
  - Common impurities: Fe,Ta,Nb,Cr,V,Sn

Schulz et al. 2017 – USGS PP1802-U

Titanium-bearing minerals



Schulz et al. 2017 – USGS PP1802-T

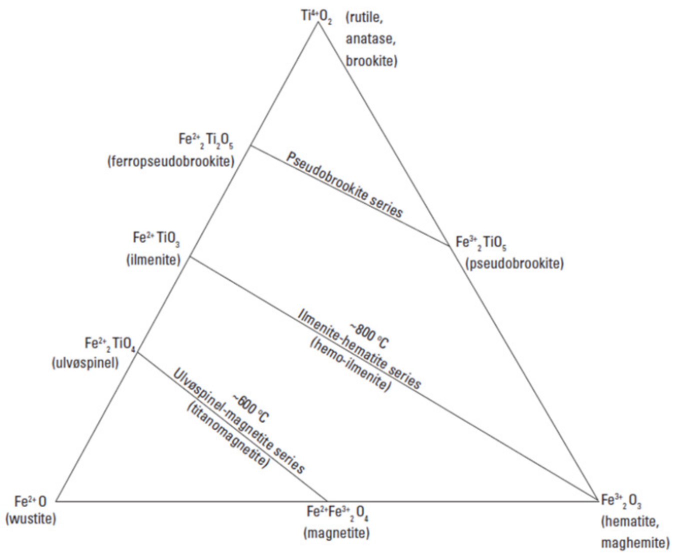
Natural Resources Canada / Ressources naturelles Canada

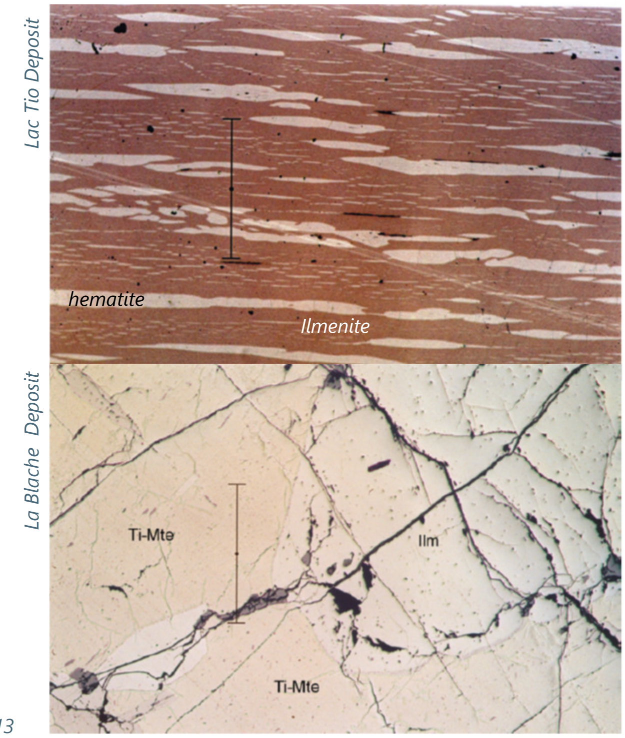
Canada

7

Mineralogy

Ternary Plot Ti^{4+}-Fe^{2+}-Fe^{3+}



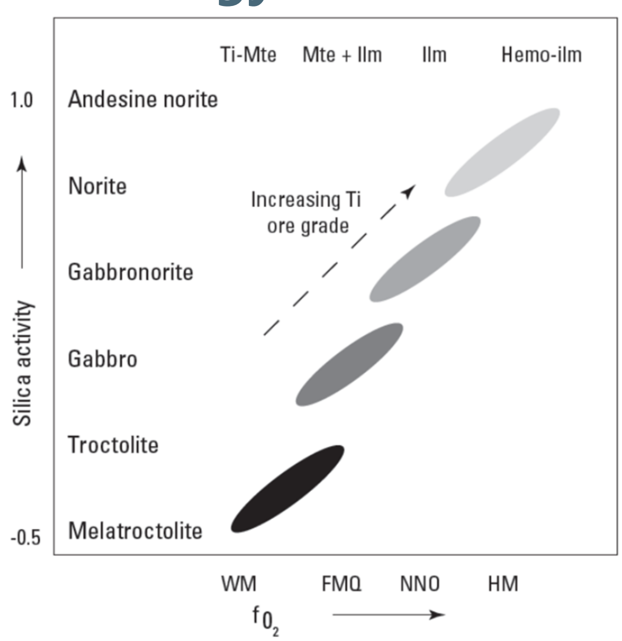


Natural Resources Canada   Ressources naturelles Canada

Woodruff et al. 2013

8

Mineralogy



- ***Oxygen fugacity*** and ***silica activity*** of anorthosite ***play a critical role*** controlling ***oxide mineralogy***
- Assimilation of silica-rich rocks by ascending and differentiating mafic magma can increase oxygen fugacity, consuming magnetite and making ilmenite more abundant as well as increasing the hematite component of ilmenite
- The control exerted by redox conditions and silica activity corroborates observations by Anderson and Morin (1969) of ***the dominance of titaniferous magnetite*** in ***labradorite-type*** anorthosite plutons versus the ***dominance of hemo-ilmenite*** in ***andesine-type*** anorthosite plutons.

Natural Resources Canada   Ressources naturelles Canada

Woodruff et al. 2013

Canada

Classification Scheme for V and Ti Deposits

Vanadium

- **Vanadiferous Titanomagnetite Deposits**
  - *Magnetite-ilmenite dominant minerals*
  - *Hematite, perovskite, rutile present in some deposits*
- Sandstone-Hosted Vanadium Deposits
- Shale-Hosted Vanadium Deposits
- Vanadate Deposits
- Other Magmatic-Hydrothermal Vanadium Resources
- Fossil Fuels

Schulz et al. 2017 – USGS PP1802-U

Titanium

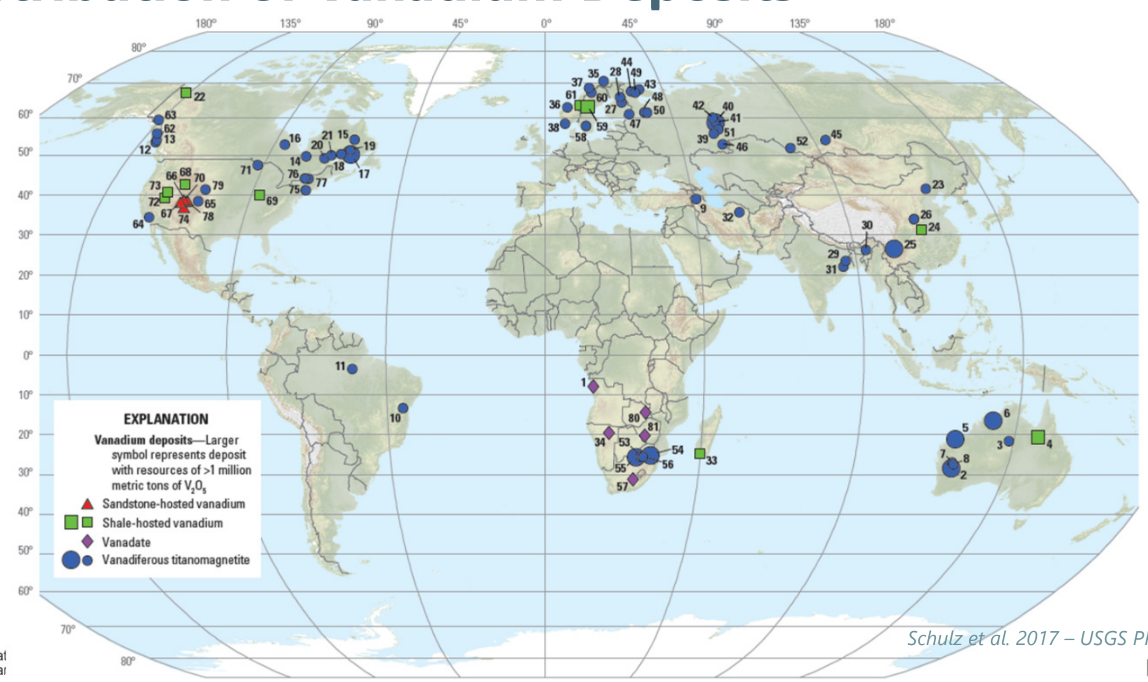
- **Igneous Deposits**
  - *Massif anorthosite – Hemo-ilmenite (very high)*
  - *Anorthosite-gabbro – Ilmenite, titanomagnetite (high)*
  - *Layered mafic intrusion – Ilmenite, titanomagnetite (high)*
  - *Troctolite/ultramafic – Ilmenite, titanomagnetite*
  - *Albitic/metasomatized – Rutile*
  - *Alkalic/metasomatized – Perovskite, brookite, rutile*
  - *Weathered alkali rocks – Anatase*
  - *Weathered anorthositic rocks – Ilmenite, rutile*
- Metamorphic Deposits
- Sedimentary/heavy mineral Deposits

Schulz et al. 2017 – USGS PP1802-T

Natural Resources Canada Ressources naturelles Canada

Canada

Distribution of Vanadium Deposits



Schulz et al. 2017 – USGS PP1802-U

11

Distribution of Titanium Deposits

Schulz et al. 2017 – USGS PP1802-T

12

Classification Scheme for Fe-Ti-V-(P) Deposits

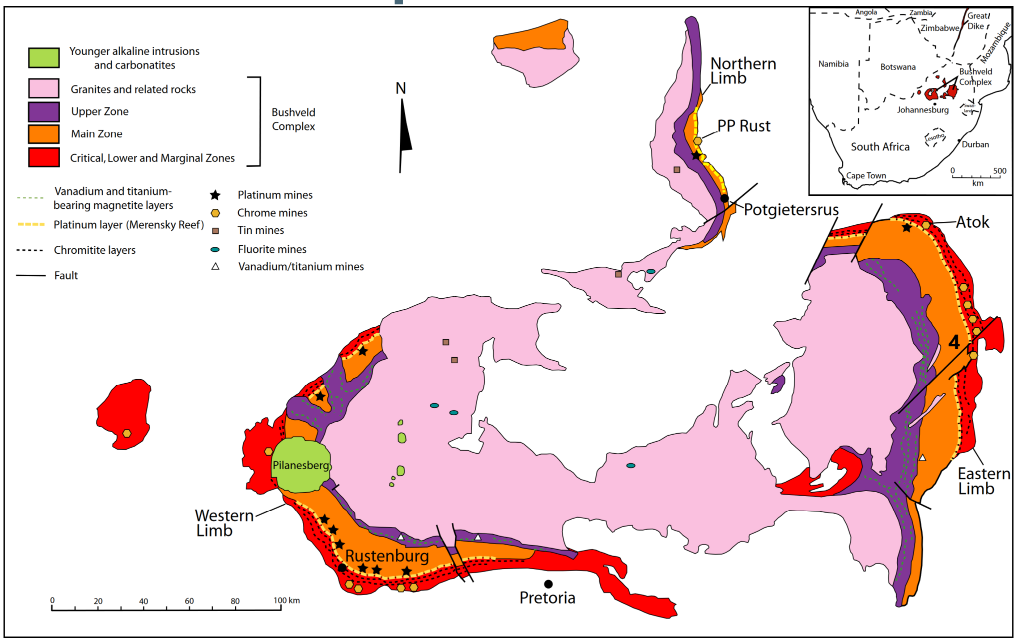
Enrichment of magnetite, titanomagnetite, and ilmenite may occur in both ultramafic and mafic rock types and several distinct types of deposits occurred and may be classified in many ways

- Upper Parts of Large Layered Complexes
  - Examples: Bushveld Complex (South Africa), Windimurra Complex (Australia), Lac Doré Complex-? (Canada)
- Flood basalt-related/Greenstone belt-related deposits
  - Panzhihua, Hongge, Baima, Taihe (Emeishan LIP – China), Ring of Fire prospects-? (Canada)
- Anorthosite-related deposits: Proterozoic Anorthosite Complexes
  - Examples: Lac Tio (Canada), Tellnes (Norway), Damiao (China), St-Urbain (Canada)
- Alaskan-Urals Type-related deposits
  - Examples: Kachkanar (Russia)

Modified from Pang et al. 2010 - Lithos

Natural Resources Canada Ressources naturelles Canada Canada

Bushveld Complex – South Africa



World Mineral Treasure: Bushveld Igneous Complex

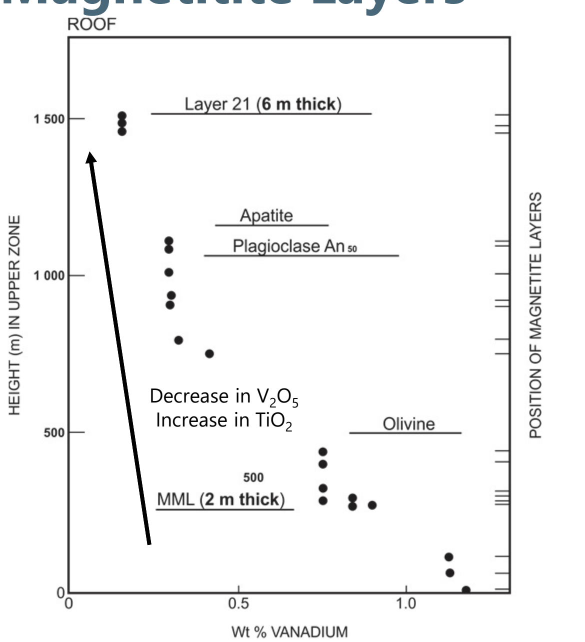
- World's largest layered mafic-ultramafic complex
  - Covering 66,000 km²
- World largest chromite and PGEs resources
  - Chromite is confined within the Critical Zone
  - PGE is confined at the top of the Critical Zone near the Main Zone
- V mineralization occur throughout the Upper Zone
- Continuous over 100s km

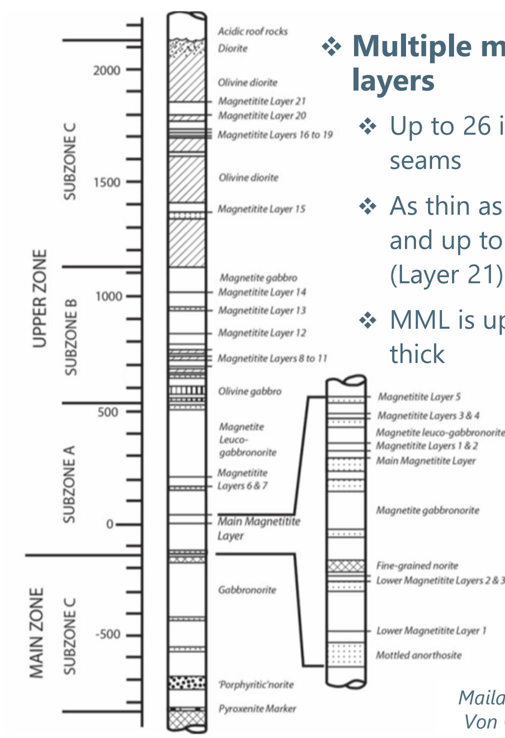
Natural Resources Canada | Ressources naturelles Canada

Taylor et al. 2009 – USGS

Canada

Magnetitite Layers





- **Multiple magnetite layers**
  - Up to 26 individual seams
  - As thin as 2 cm-thick and up to 7.1 m thick (Layer 21)
  - MML is up to 2.5 m thick

Natural Resources Canada | Ressources naturelles Canada

Cawthorn 2015 – CGSA

Maila 2015; Harney and Von Gruenewaldt, 1995

15

Main Magnetite Layer

Scoon & Mitchell - 2012

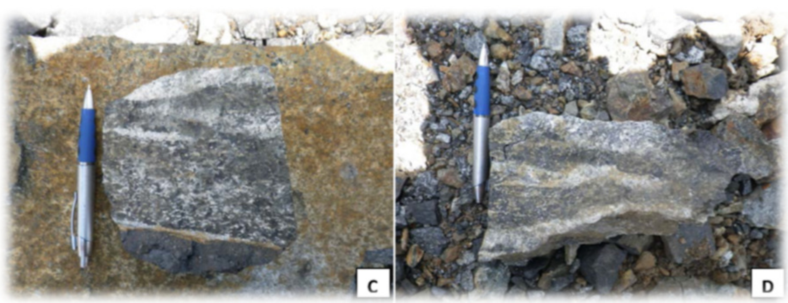
Natural Resources Canada Ressources naturelles Canada

Typical textural facies within the Main Magnetite Layer – Magnet Heights

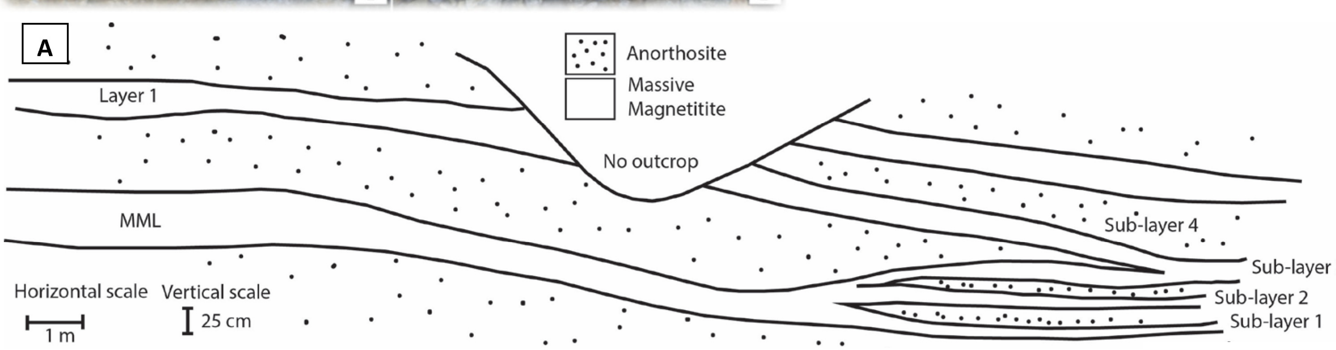
Photos (central and right ones) from C. Rowan - 2008

16

Magnetitite Layers



- **Magnetitite bifurcations**
  - Sketch of MML spitting into three sub-layers and merging with layer 1
  - Small scale magnetite bifurcation in samples

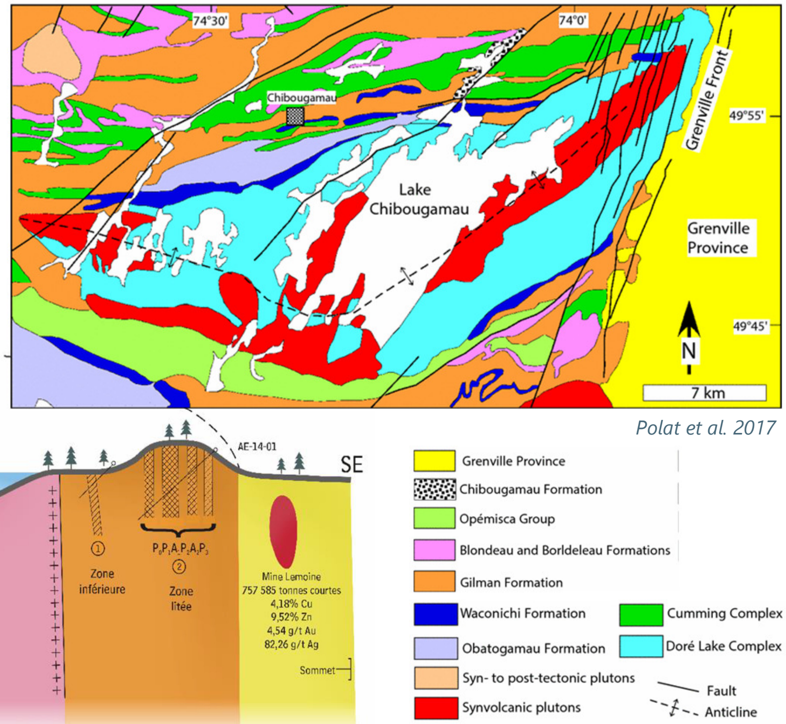


Maila 2015 - Thesis

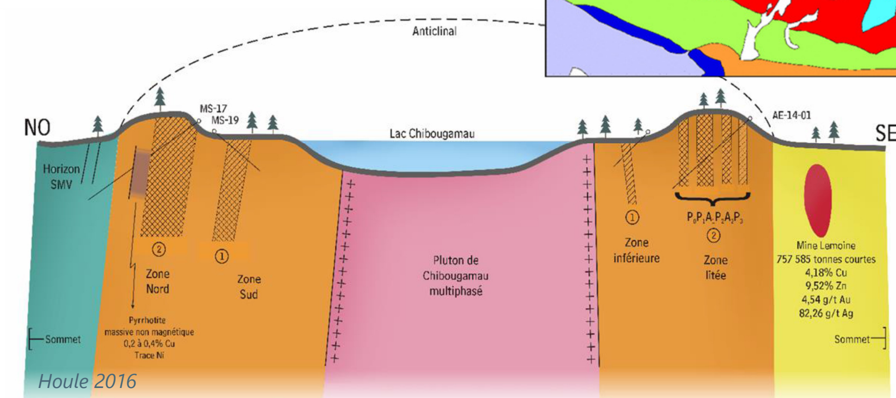
17

Lac Doré Complex

- **Large layered intrusion**
  - Fe-Ti-V mineralization occur on both limbs of the anticline
  - However, the south limb is where the best mineralization is found and contain several deposits



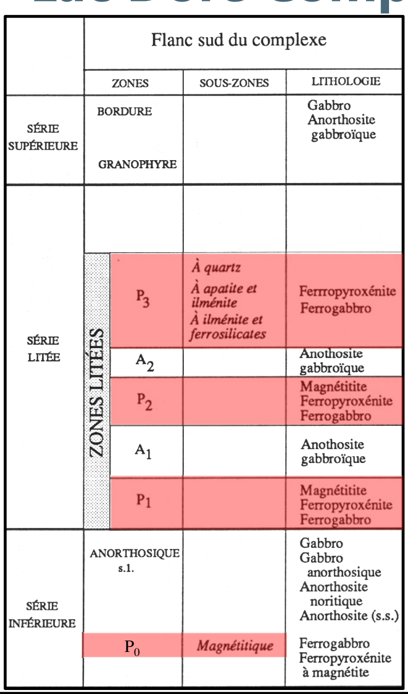
Polat et al. 2017



Houle 2016

18

Lac Doré Complex - Stratigraphy



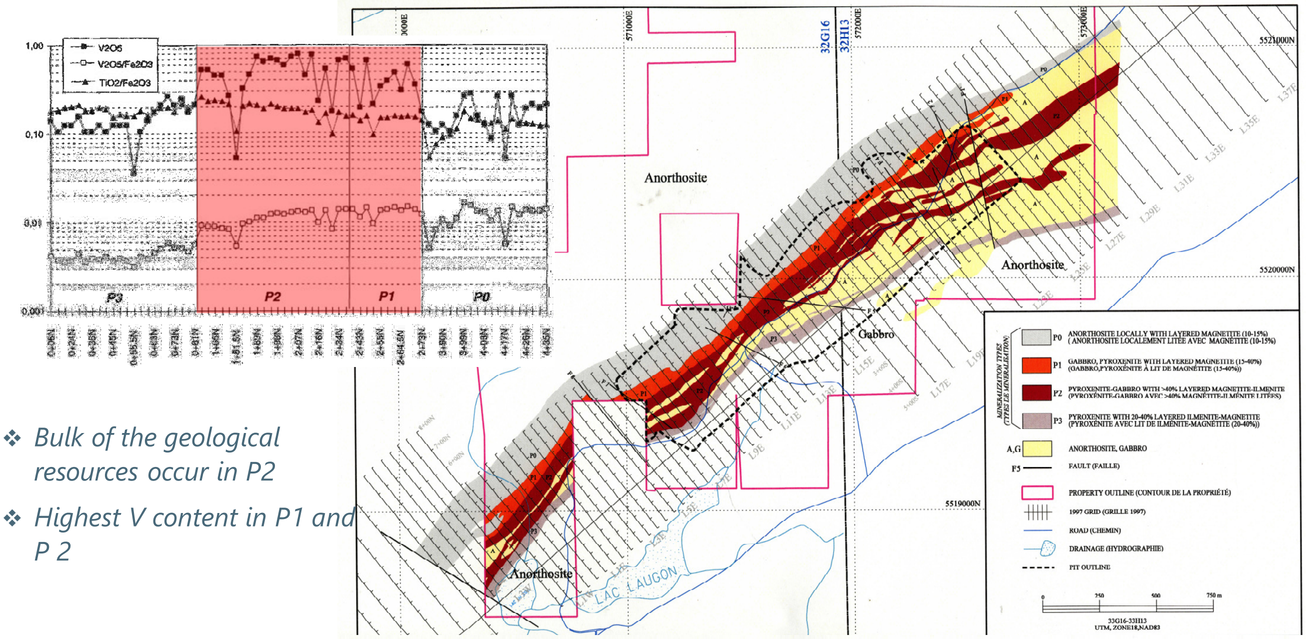
- **P0:** Anorthositic sequence locally with layered magnetitite (10-15%)
- **P1:** Layered sequence of anorthosite, gabbro and pyroxenite interlayered with magnetitite layers (15-40%). Highest V content
- **P2:** Pyroxenitic and gabbroic sequence with abundant interlayering of massive to semi-massive magnetite-ilmenite layers (>40%) and magnetite/ilmenite-bearing ferrogabbro.
- **P3:** Magnetite/ilmenite bearing ferrogabbroic sequence interlayered with magnetite/ilmenite layers (20-40%)

	Thickness as calculated from sampling	V_2O_5	Fe_2O_3	TiO_2	% Mgt from visual estimation
P0	32 m	0.194%	20.1%	1.74%	10%
P1	49 m	0.340%	41.5%	4.27%	15-30%
P2	97 m	0.486%	9.20%	9.20%	>40%
P3	38 m	0.163%	48.6%	6.43%	20-30%
Total	216 m	0.353%	49.8%	6.49%	

Daigneault et Allard, 1990; Girard and Allard 1998; Girard and D'Amours 2015

19

Lac Doré Complex – Ore Zone



- Bulk of the geological resources occur in P2
- Highest V content in P1 and P 2

Natural Resources Canada / Ressources naturelles Canada

Girard and Allard 1998; Girard and D'Amours 2015

20

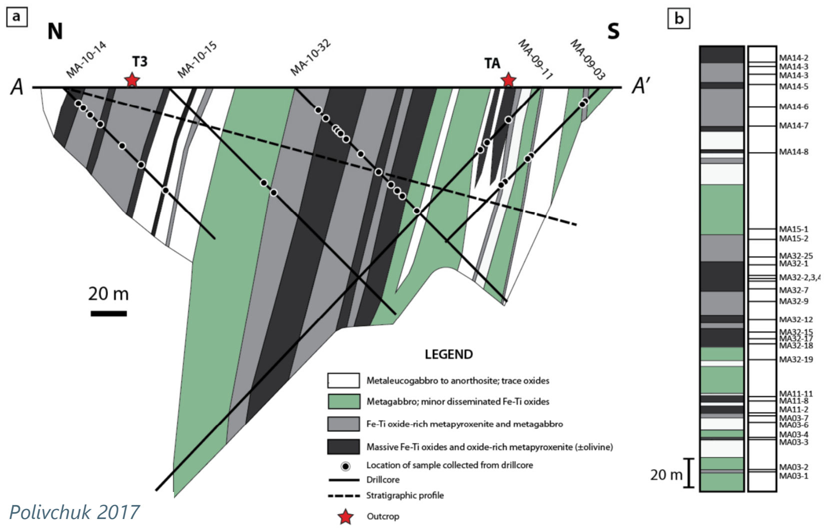
Typical Fe-Ti-V Mineralization in P_2

Natural Resources Canada / Ressources naturelles Canada

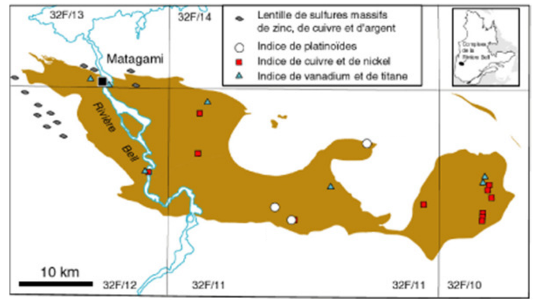
Canada

Rivière Bell Complex

Iron-T deposit is hosted by magnetite-ilmenite pyroxenites and gabbros



Polivchuk 2017

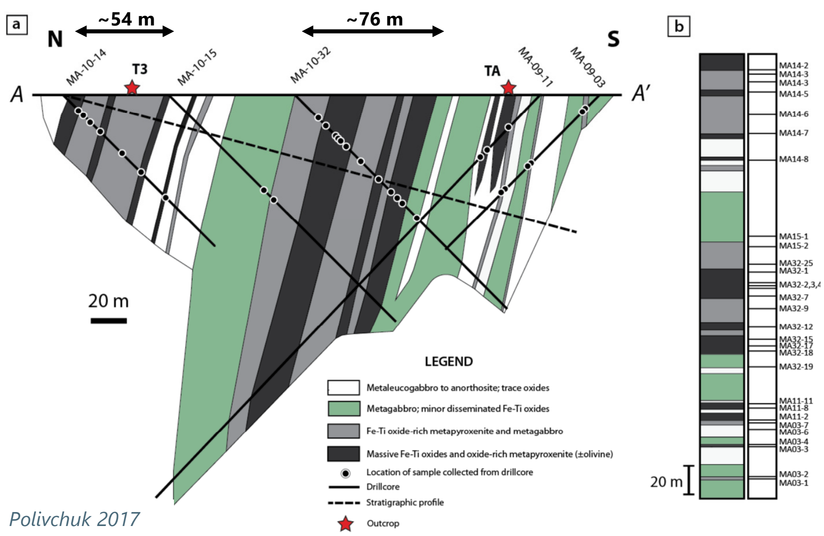


Goutier 2015

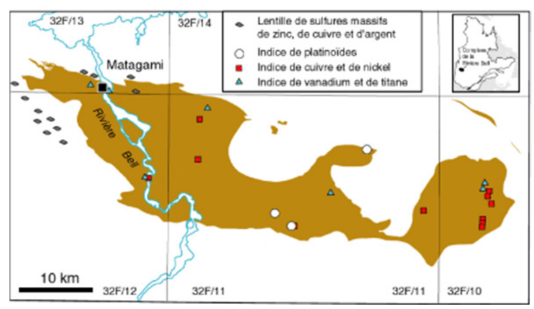
Iron-T deposit is hosted by magnetite-ilmenite pyroxenites and gabbros

Rivière Bell Complex

- The oxide-rich gabbro horizons varying in width form 10 to 100 m clearly appear on the airborne regional magnetic survey
- *Iron-T deposit is hosted by magnetite-ilmenite pyroxenites and gabbros*



Polivchuk 2017



Goutier 2015

- The oxide-rich gabbro is a mineralized cumulate forming either homogeneous horizons with disseminated oxide mineral contents ranging from 20 to 60% or homogeneous massive layers with oxide mineral contents varying from 60 to 90%
- Massive oxide mineralized bands are interlayered with poorly mineralized gabbro forming pluri-centimetric to decimetric scale interlayers

Taner et al. 1998

23

Rivière Bell Complex

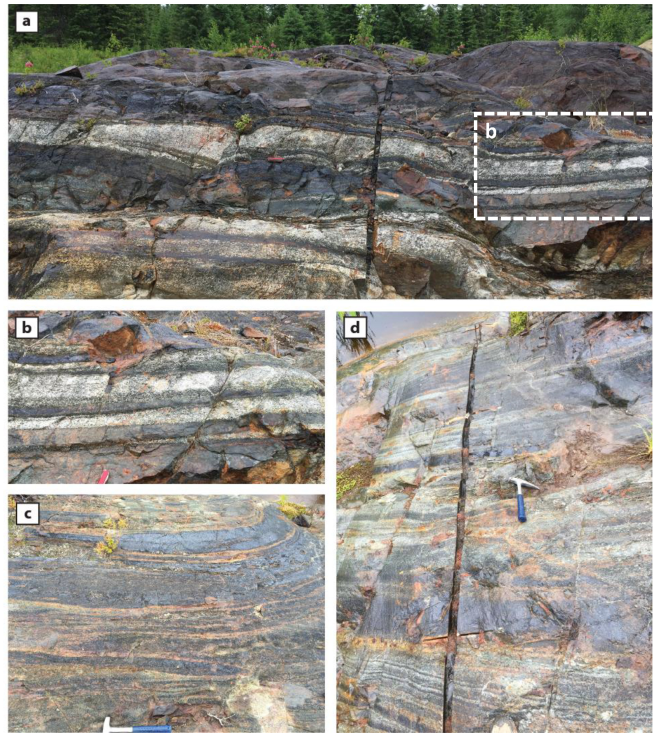
Igneous layering textures of the RBC within the Iron-T property at outcrop T3

a. Interlayered centimeter-to-decimeters thick, variably oxide-rich metaleucogabbro (speckled white layers) and metapyroxenite (dark green-grey layers). Swiss army knife for scale

b. Close-up of a sequence of several centimeters-thick oxide-rich pyroxenites and leucogabbros. Melanocratic bands exhibit both sharp and modally graded upper contacts with overlying leucogabbros. Note the tapering lowermost leucocratic band

c. Discontinuous ribbon-like banded massive oxides and gabbros. Massive oxides exhibit sharp upper and lower contacts

d. Cyclically layered magnetite gabbro. Some layers exhibit internal normal grading of oxides and mafic minerals.

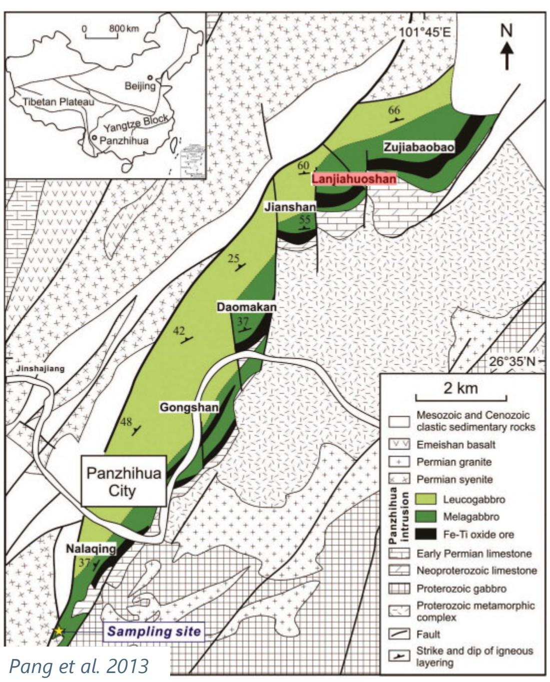


Polivchuk 2017

rces Ressources naturelles Canada

24

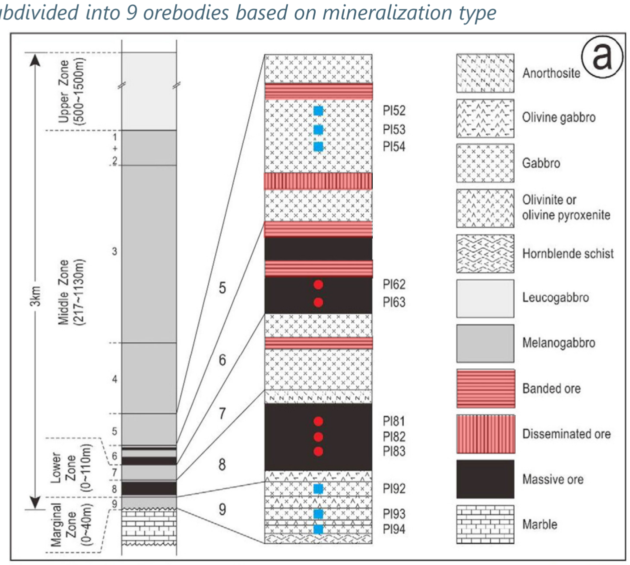
Panzhihua Intrusion



Pang et al. 2013

From the base upwards, the Panzhihua intrusion is divided into four zones based on textural features and cumulus minerals

- Marginal Zone; Lower Zone; Middle Zone; and Upper Zone
- *Subdivided into 9 orebodies based on mineralization type*

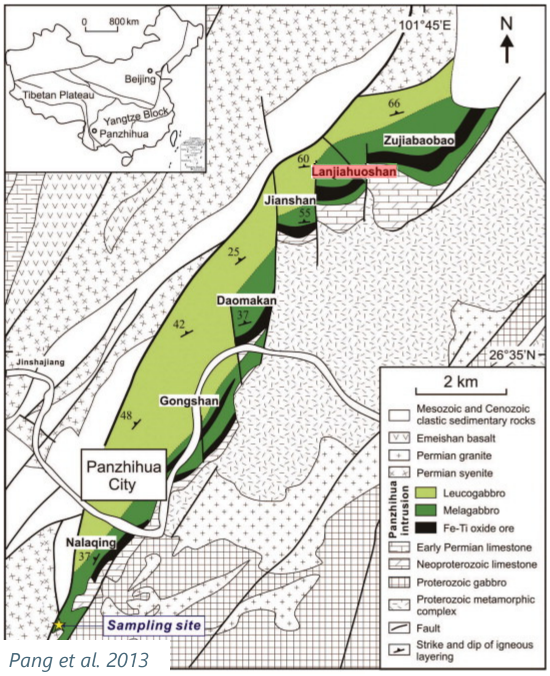


Gao et al. 2017

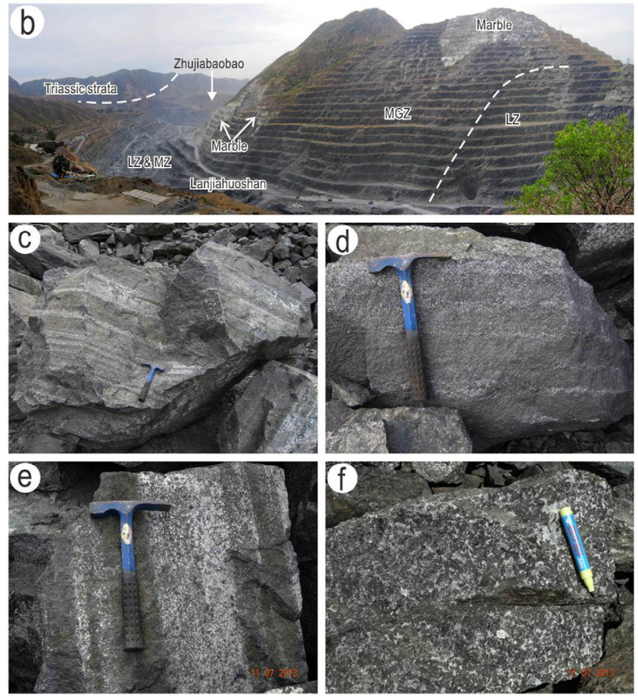
Canada

25

Panzhihua Intrusion



Pang et al. 2013

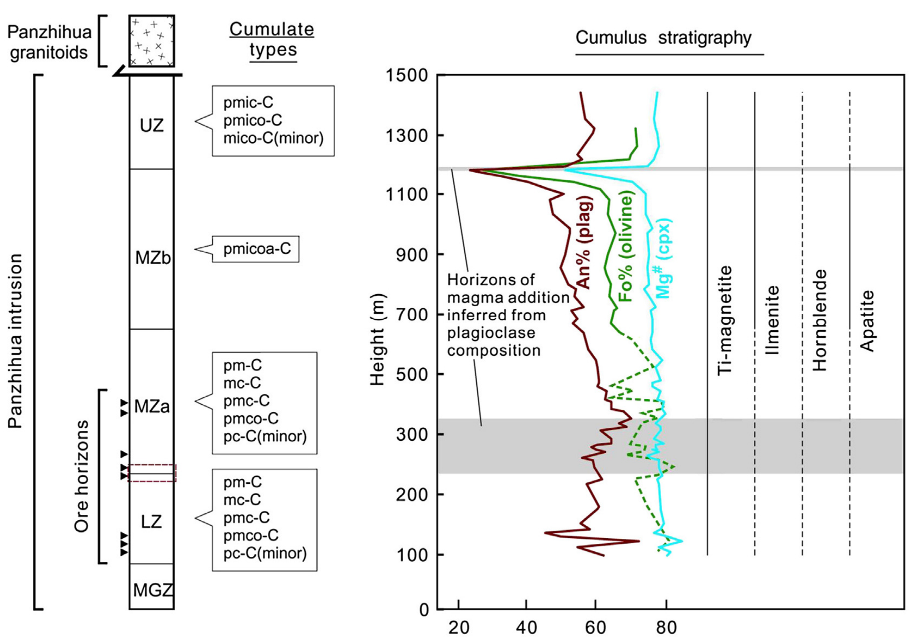


Gao et al. 2017

Canada

26

Panzhihua Intrusion



Natural Resources Canada / Ressources naturelles Canada

Simplified stratigraphic column of the Panzhihua intrusion

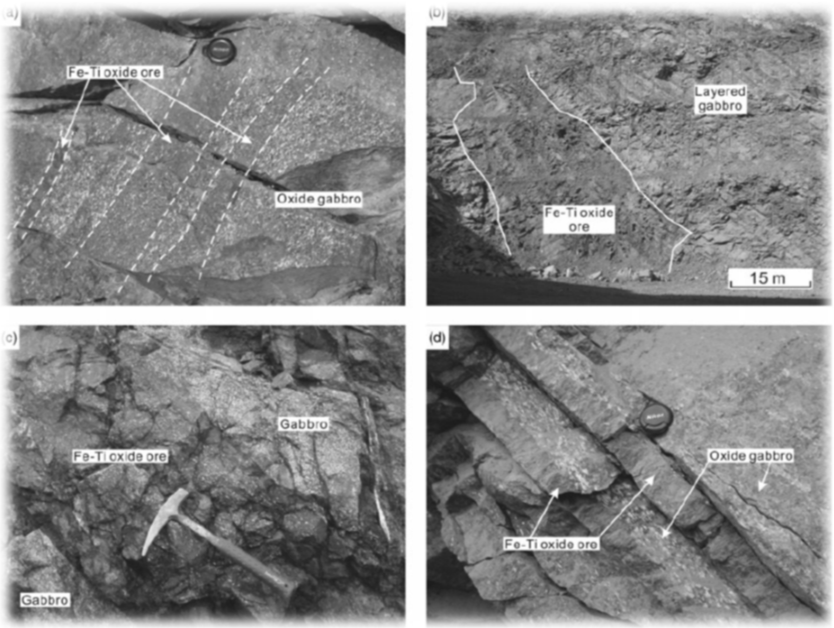
- showing the zonal division and the variations in cumulate types, cumulus minerals and their compositions.
- The cumulate nomenclature
  - "-C" meaning cumulus:
  - Plagioclase (p)
  - magnetite (m)
  - ilmenite (i)
  - clinopyroxene (c)
  - olivine (o)
  - apatite (a).

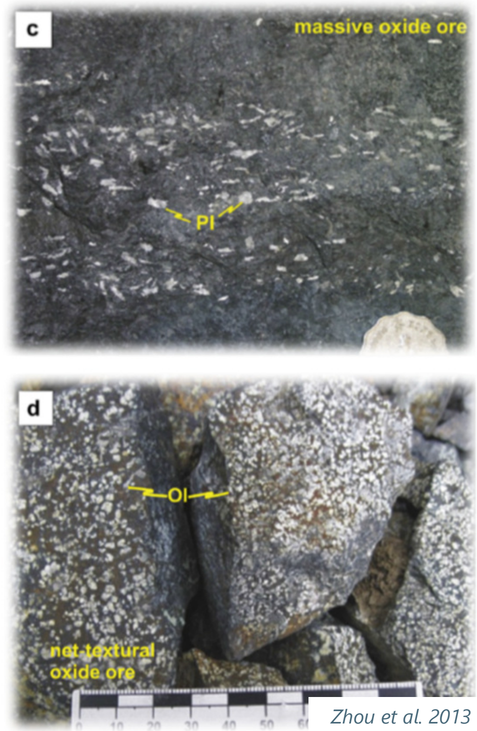
Pang et al. 2013

Canada

27

Panzhihua Intrusion



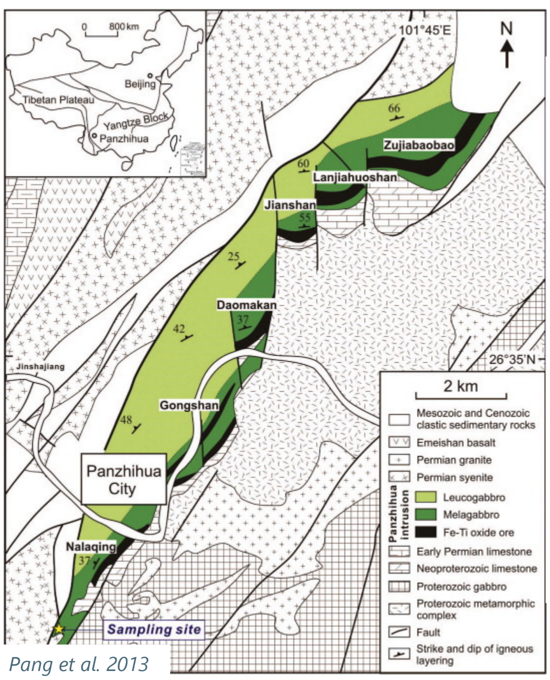


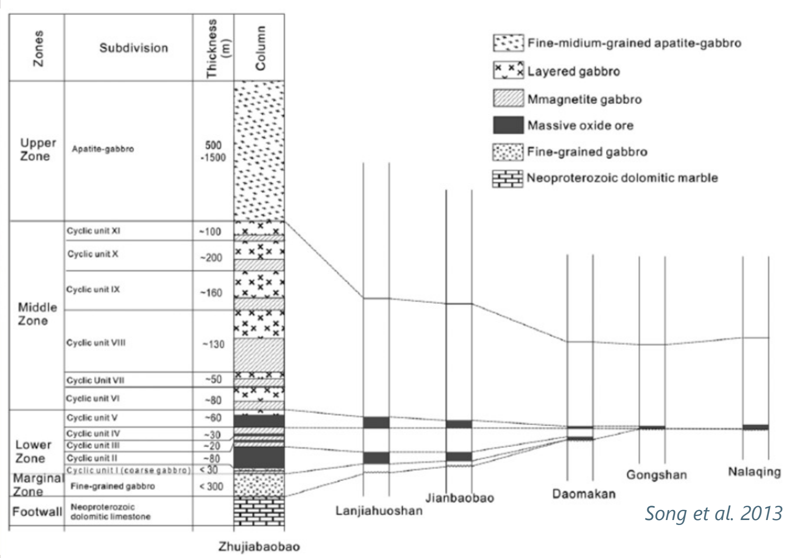
Pang et al. 2008

Zhou et al. 2013

28

Panzhihua Intrusion

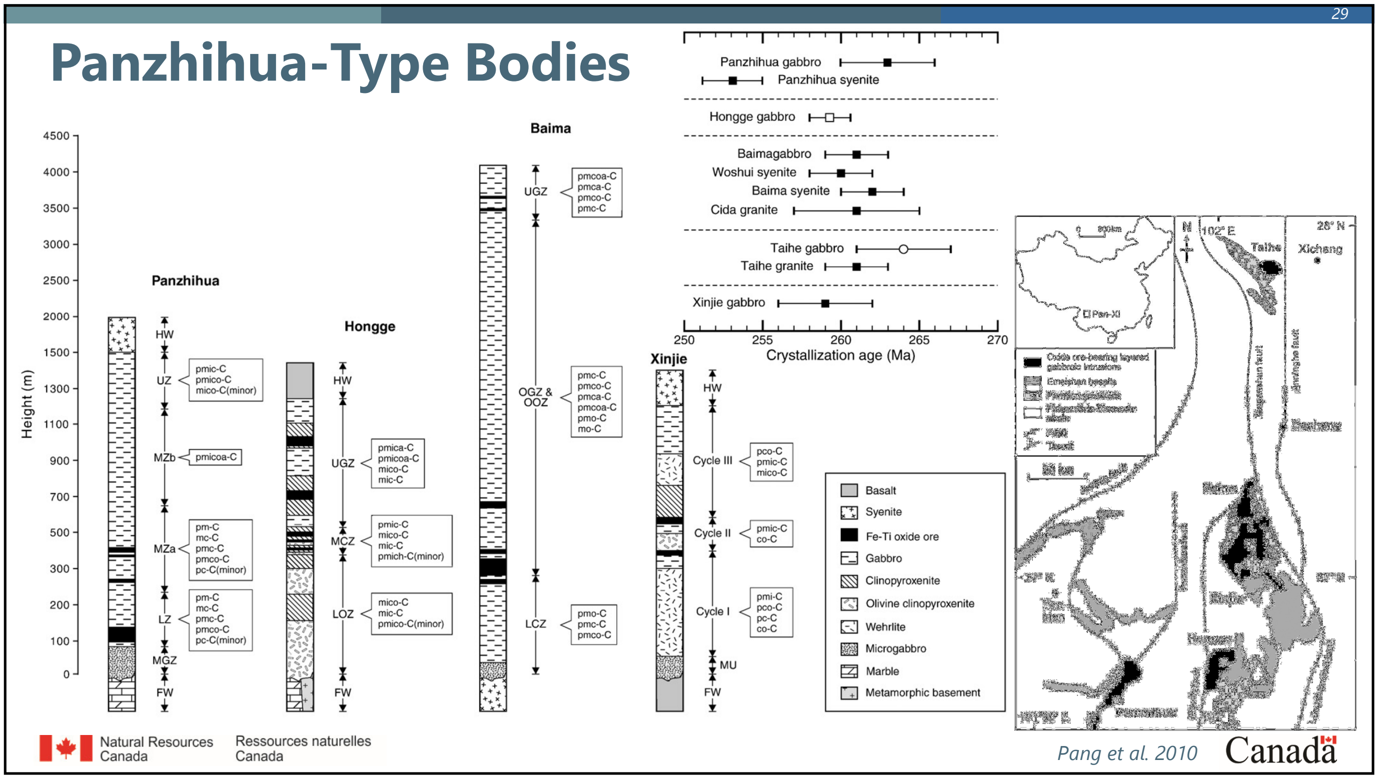


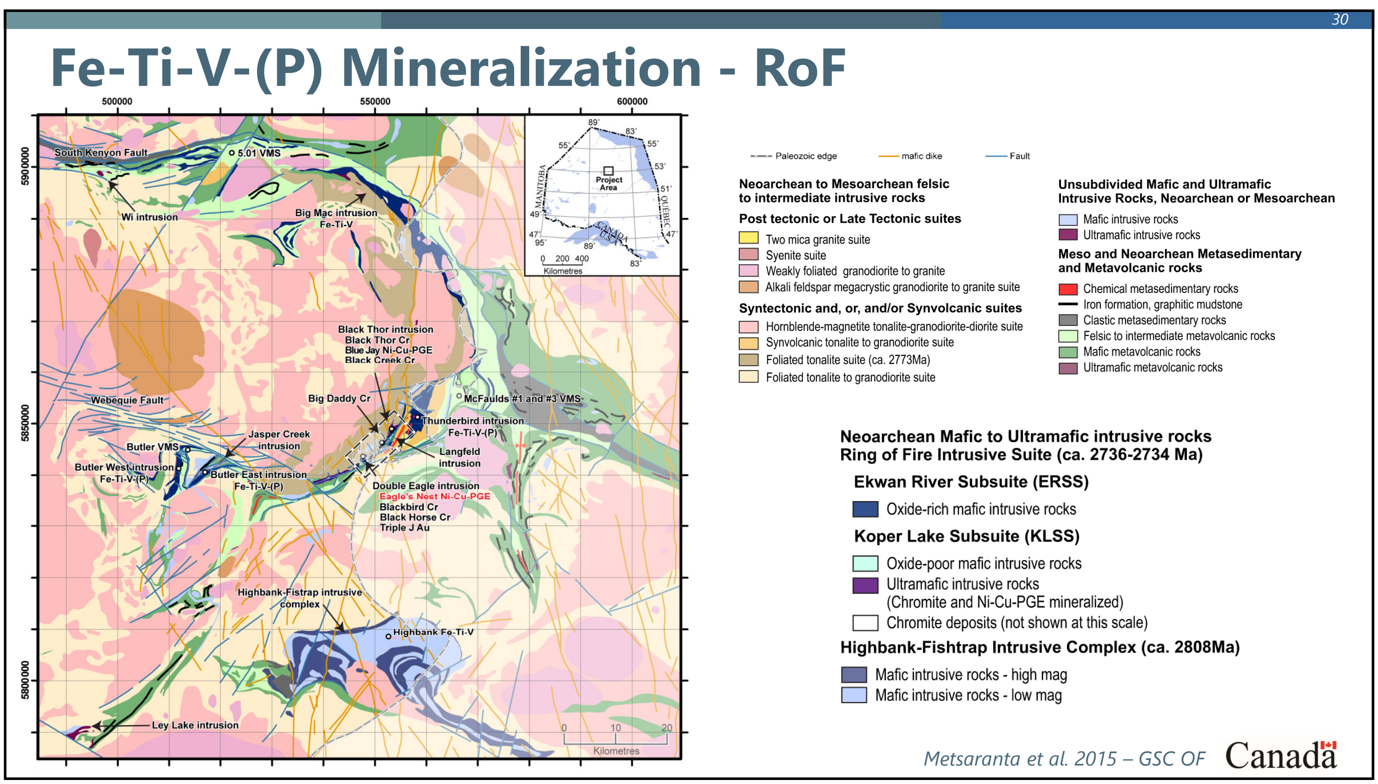


Pang et al. 2013

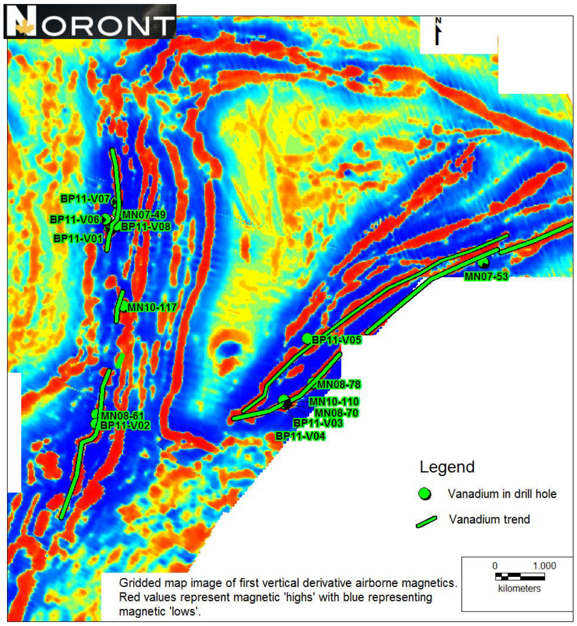
Song et al. 2013

Canada


29
Panzhihua-Type Bodies
Panzhihua gabbro
Panzhihua syenite
Hongge gabbro
Baimagabbro
Woshui syenite
Baima syenite
Cida granite
Taihe gabbro
Taihe granite
Xinjie gabbro
250 255 260 265 270
Crystallization age (Ma)
Height (m)
Panzhihua
Hongge
Baima
Xinjie
HW
UZ
MZb
MZa
LZ
MGZ
FW
UGZ
MCZ
LOZ
OGZ & OOZ
LCZ
Cycle III
Cycle II
Cycle I
MU
Basalt
Syenite
Fe-Ti oxide ore
Gabbro
Clinopyroxenite
Olivine clinopyroxenite
Wehrlite
Microgabbro
Marble
Metamorphic basement
102° E
28° N
Taihe
Xichang
Natural Resources Canada
Ressources naturelles Canada
Pang et al. 2010
Canada


30
Fe-Ti-V-(P) Mineralization - RoF
500000
550000
600000
5900000
5850000
5800000
South Kenyon Fault
5.01 VMS
Wi intrusion
Big Mac intrusion Fe-Ti-V
Black Thor intrusion
Black Thor Cr
Blue Jay Ni-Cu-PGE
Black Creek Cr
Webequie Fault
Big Daddy Cr
McFaulds #1 and #3 VMS
Thunderbird intrusion Fe-Ti-V-(P)
Jasper Creek intrusion
Butler VMS
Butler West intrusion Fe-Ti-V-(P)
Butler East intrusion Fe-Ti-V-(P)
Langfeld intrusion
Double Eagle intrusion
Eagle's Nest Ni-Cu-PGE
Blackbird Cr
Black Horse Cr
Triple J Au
Highbank-Fistrap intrusive complex
Highbank Fe-Ti-V
Ley Lake intrusion
Project Area
MANITOBA
QUEBEC
Kilometres
Paleozoic edge
mafic dike
Fault
Neoarchean to Mesoarchean felsic to intermediate intrusive rocks
Post tectonic or Late Tectonic suites
Two mica granite suite
Syenite suite
Weakly foliated granodiorite to granite
Alkali feldspar megacrystic granodiorite to granite suite
Syntectonic and, or, and/or Synvolcanic suites
Hornblende-magnetite tonalite-granodiorite-diorite suite
Synvolcanic tonalite to granodiorite suite
Foliated tonalite suite (ca. 2773Ma)
Foliated tonalite to granodiorite suite
Unsubdivided Mafic and Ultramafic Intrusive Rocks, Neoarchean or Mesoarchean
Mafic intrusive rocks
Ultramafic intrusive rocks
Meso and Neoarchean Metasedimentary and Metavolcanic rocks
Chemical metasedimentary rocks
Iron formation, graphitic mudstone
Clastic metasedimentary rocks
Felsic to intermediate metavolcanic rocks
Mafic metavolcanic rocks
Ultramafic metavolcanic rocks
Neoarchean Mafic to Ultramafic intrusive rocks
Ring of Fire Intrusive Suite (ca. 2736-2734 Ma)
Ekwan River Subsuite (ERSS)
Oxide-rich mafic intrusive rocks
Koper Lake Subsuite (KLSS)
Oxide-poor mafic intrusive rocks
Ultramafic intrusive rocks
(Chromite and Ni-Cu-PGE mineralized)
Chromite deposits (not shown at this scale)
Highbank-Fishtrap Intrusive Complex (ca. 2808Ma)
Mafic intrusive rocks - high mag
Mafic intrusive rocks - low mag
Metsaranta et al. 2015 – GSC OF
Canada

Fe-Ti-V-(P) Mineralization – Butler Area

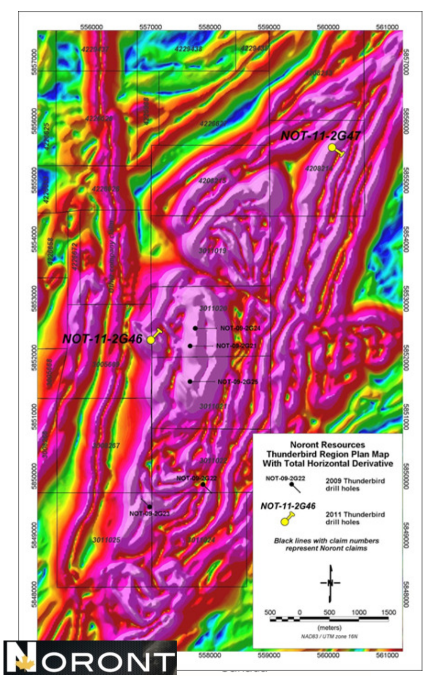


- ❖Several Fe-Ti-V mineralized horizons
  - ❖Both flanks (Western & Eastern)
- ❖Fe-Ti-V mineralization
  - ❖1.17% V2O5, 7.97% TiO2 and 40.73% Fe over 4.2 m as higher grade intersection
  - ❖0.54% V2O5, 0.46% TiO2 and 23.78% Fe over 36 m as a wider, lower grade

Natural Resources Canada   Ressources naturelles Canada

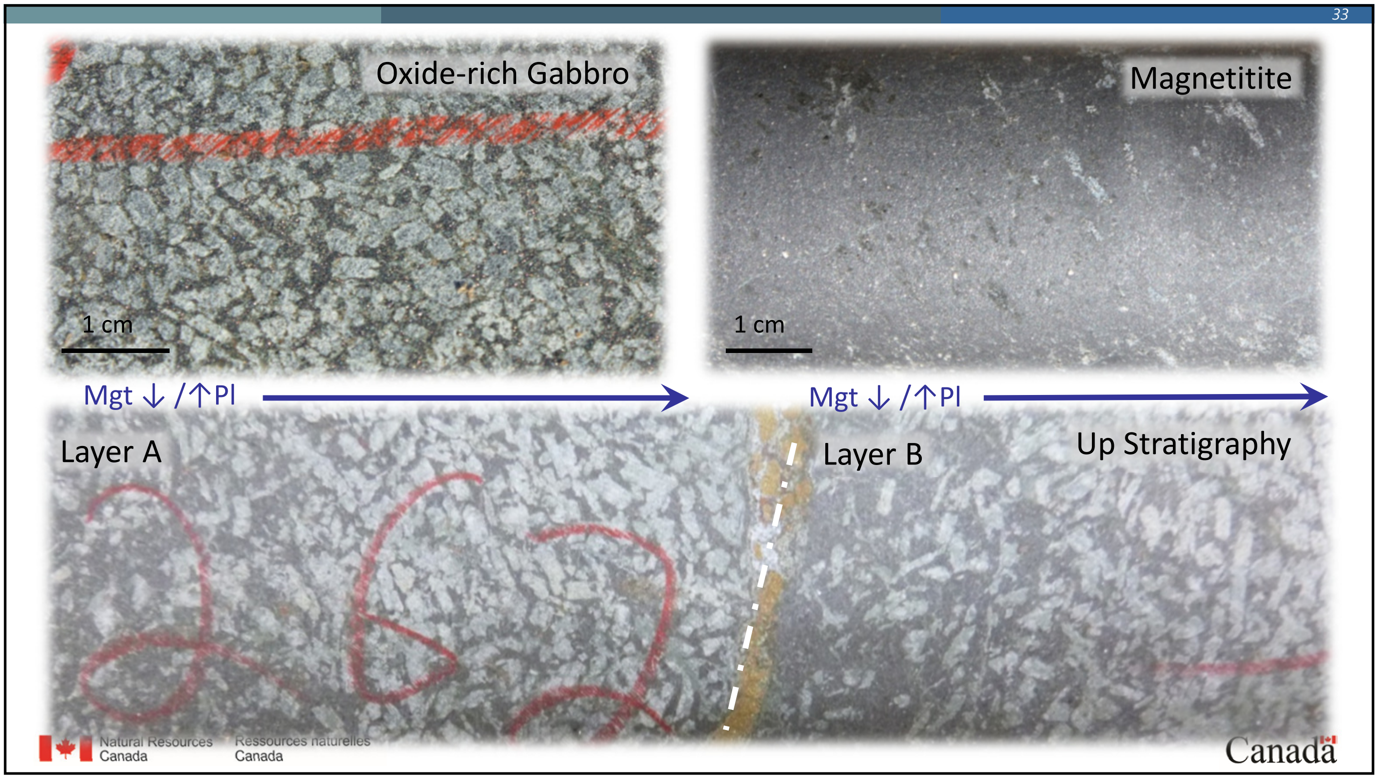
Canada

Fe-Ti-V-(P) Mineralization – Thunderbird Area



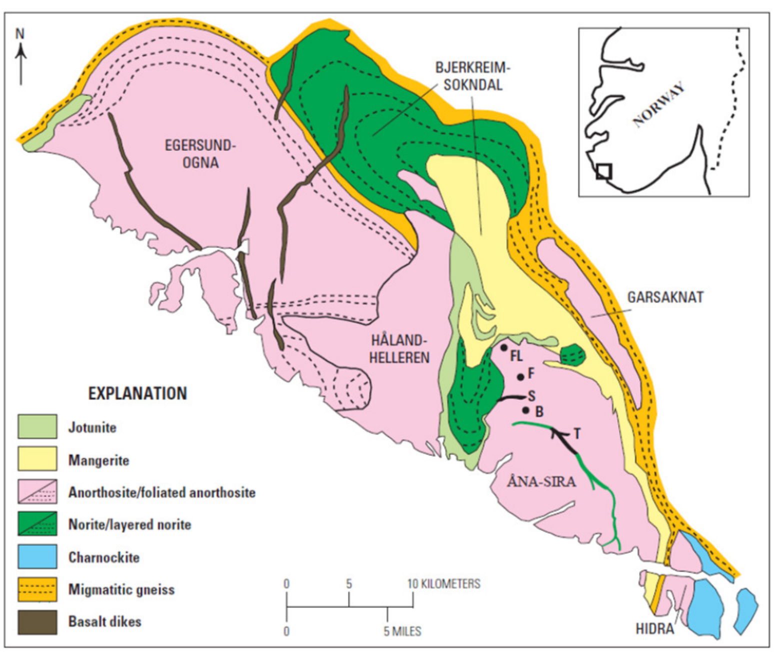
- ❖**Fe-Ti-V mineralized horizons**
  - ❖0.36% V2O5 over 178 m including higher grade @ 0.62% V2O5 over 16 m
  - ❖0.37% V2O5 over 100 m including higher grade @ 0.57% V2O5 over 21 m
- ❖ Two main mineralized intervals
  - ❖ Structural repetition of the same mineralized interval
- ❖Fe-Ti-P mineralized horizons outward
- ❖ Presence of a fold axis in the middle of the Thunderbird intrusion
  - ❖**Based on geochemistry profile, mineral chemistry, and assays profiles**

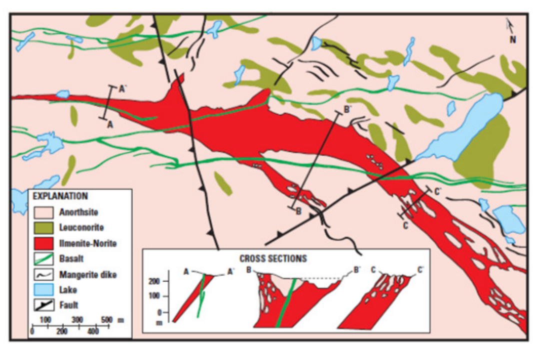
Canada



Rogaland Anorthosite

- Rogaland Anorthosite
  - Includes 4 Anorthositic Massifs and 1 layered intrusion
  - Contains 5 deposits (AS Massif) and 7 deposits (HH Massif)
  - Dominated by hemo-ilmenite oxides





Iron- titanium-oxide deposits:
T=Tellnes
B=Blåfjell, S=Storgangen,
F=Flordalen, and Fl=Frøtlog

Woodruff et al. 2013

Canada

Fe-Ti Deposits within Rogaland Anorthosite

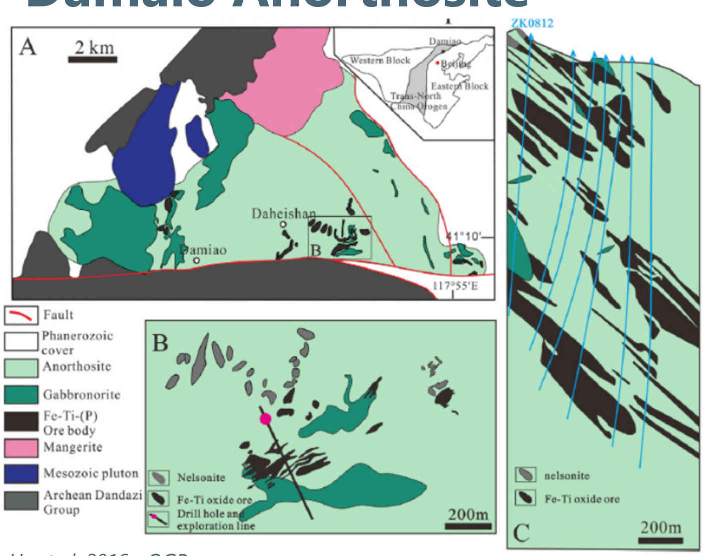
Table 3 Principal characters of the Fe-Ti high-grade deposits in Rogaland

Name	Setting	Rock type	Oxide paragenesis	Suggested origin
Tellnes (T)	Dyke-like intrusion in ÅS anorthosite	Homogeneous ilmenite norite, locally laminated	Hemo-ilmenite ± magnetite	Cumulate enriched by crystal sorting in a noritic liquid
Blåfjell (B) Laksedal (L)	Bodies in noritic pegmatite intruded in ÅS	Massive ilmenite	Hemo-ilmenite (Cr-, V-, Mg-rich) ± magnetite (only in L)	Cumulate in a noritic liquid
Storgangen (S)	Concordantly layered dyke intruded in ÅS	Melanoritic layers in slightly deformed layered norite	Hemo-ilmenite + Cr-, V-rich magnetite	Cumulate in differentiated sill
Kydlandsvatn (Ky)	Strongly dipping ilmenite lenses and layers in the contact zone between EGOG and HH	Ilmenite layers in layered anorthosite and leuconorite	Hemo-ilmenite (medium in Cr, V, Mg) ± magnetite	Cumulate in a differentiated sill plastically deformed by the anorthosite emplacement process
Svånes (Sv)	Deformed layered body intruded in HH	Same	Hemo-ilmenite (medium in Cr, V, Mg)	Same
Rødemyr I (RI)	Dyke intruded in HH close to the contact with the NGZ	Oxide minerals vein	Hemo-ilmenite (low Cr) + magnetite (V-rich)	Probably cumulate
Rødemyr II (RII) Kagnuden (Ka)	Raft in the NGZ (RII) or at the contact with HH	Oxide-rich lenses	Ilmenite (low Cr) + Ti-magnetite + apatite (medium REE)	Cumulate or immiscibility
Hestnes (H) Eigerøy (E)	Veins intruded in HH	Vein of nelsonite with planar orientation of apatite and oxide mineral	Ilmenite (Cr-poor) + Ti-magnetite + apatite (REE-rich)	Immiscibility of a P-, Ti-, Fe-rich liquid
Jerneld (J)	Veins in HH	Massive hemo-ilmenite	Hemo-ilmenite (very Cr-, Mg-rich)	High temperature solid state segregation and recrystallisation (dynamic recrystallisation)

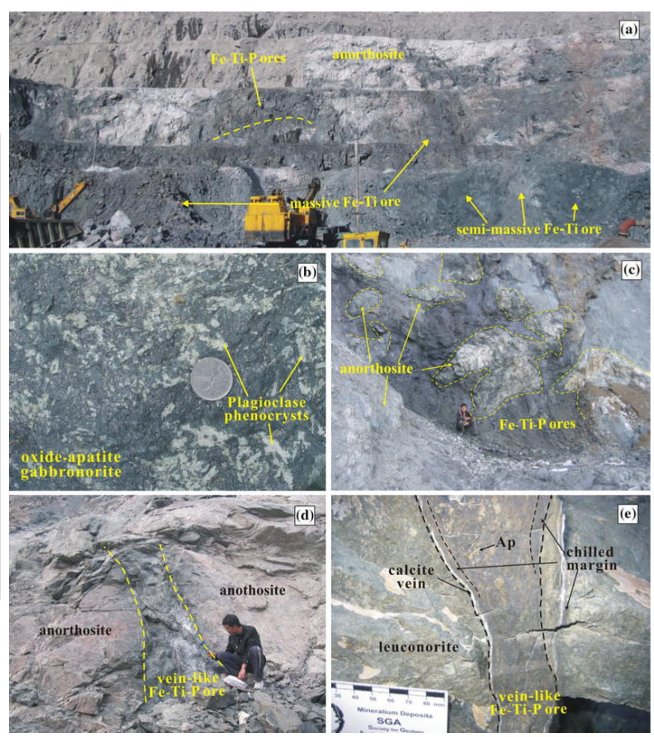
Duchesne, 1999

Natural Resources Canada | Ressources naturelles Canada | Canada

Damaio Anorthosite



He et al. 2016 - OGR



Chen et al. 2013

Natural Resources Canada | Ressources naturelles Canada

Classification Scheme for Fe-Ti-V-(P) Deposits

Major characteristics of magmatic Fe–Ti oxide deposits worldwide.

Association	Host rock	Ore occurrence	Ore mineralogy[a]	Parental magma	Example
Proterozoic anorthosite complexes	Anorthosite, leuconorite, leucogabbro, leucotroctolite	Cross-cutting, massive lenses with sharp contacts against host rocks	Hemo-ilmenite or titanomagnetite, with or without apatite	Ferrodiorite[b]	Tellnes (Norway), Lac Tio (Canada)
Upper parts of large layered complexes	Gabbronorite, ferrogabbronorite, ferrodiorite	Conformable, laterally extensive layers with either sharp or gradational contacts against host rocks	Titanomagnetite, with or without apatite	Evolved, Fe-rich tholeiite	Bushveld (South Africa), Windimurra (Australia)
Lower parts of sub-volcanic intrusions associated with flood basalts	Gabbro, ferrogabbro, ultramafic cumulates	Conformable, massive lenses or layers with either sharp or gradational contacts against host rocks	Titanomagnetite, with or without ilmenite	High-Ti ferrobasalt	Panzhihua (China), Hongge (China)

[a] Only primary ore minerals are listed.
[b] The term jotunite has also been used to denote the same type of magma.

Bulk compositions related to magmatic Fe–Ti oxide deposits.

	Fe-rich tholeiite	Ferrodiorite	Picrite	High-Ti basalts		
	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2^a	49.79	49.78	44.47	46.89	43.93	44.86
TiO^2	0.82	3.02	2.35	3.30	3.12	3.61
Al_2O_3	15.82	14.37	11.15	10.13	14.80	11.08
Fe_2O_3	1.18	2.88	1.33	1.37	1.53	1.47
FeO	11.83	13.11	12.03	12.33	13.77	13.23
MnO	0.19	0.23	0.19	0.20	0.20	0.20
MgO	6.14	3.39	14.78	10.96	7.20	8.92
CaO	10.93	7.99	11.38	10.97	10.67	9.55
Na_2O	2.97	3.29	1.89	1.44	2.24	2.55
K_2O	0.25	1.20	0.08	1.98	1.21	1.22
P_2O_5	0.07	0.74	0.34	0.43	0.33	0.52
Mg#[b]	48	32	69	61	48	55

[a] Major and minor element oxides are in weight percent and are calculated to 100% total on a volatile-free basis.
[b] $Mg\# = [molar\ 100 \times Mg/(Mg + Fe^{2+})]$, assuming 10% of total iron oxide is ferric.

Natural Resources Canada Ressources naturelles Canada

Pang et al. 2010 - Lithos

Canadä

Ore-Forming Processes - Fe-Ti-V-(P) Deposits

Several mechanisms have been proposed to explain the formation of the Fe-Ti oxide layers. Many of the processes involved are analogous to processes which have been put forward for the genesis of chromitite layers…

- ***Fractional crystallisation, crystal sorting & plagioclase buoyancy***
- ***Liquid immiscibility***
- *Magma mixing/addition*
- *Change in physical parameters*
  - *Oxygen fugacity and Pressure*
- Injection of crystal slurries
- Mobilization and Remobilization *(mainly invoke for Anorthositic Massif)*
  - Filter-press compaction, solid-state remobilization, and hydrothermal remobilization

Natural Resources Canada Ressources naturelles Canada

Canadä

Ore-Forming Processes - Fe-Ti-V-(P) Deposits

Mass-balance problem is less an issue for Fe and V in magnetite than there is for Cr in chromitite layers…

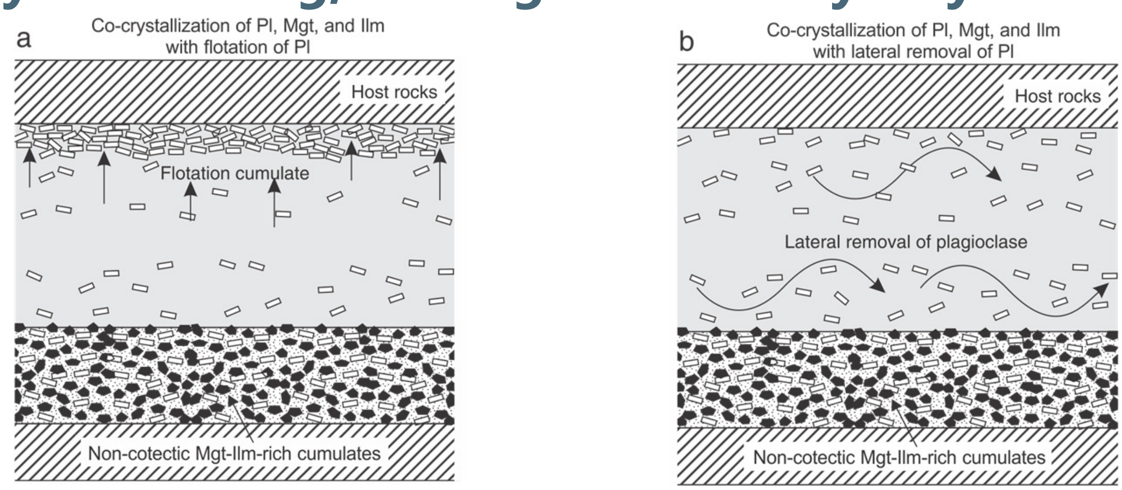
- First of all, whereas Cr is the major element in chromite, V is simply a ***strongly compatible element within the magnetite structure***, and it is the behavior and abundance of Fe that controls magnetite formation
  - For example, if Fe-rich melts contain on the order of 20 wt.% total FeO (Tegner 1997), the enrichment factor for Fe in oxide layers is only 4
- Thus, formation of a ***1-m-thick layer of oxide*** would only require the ***suspension of 8 m of silicate crystals***. Since magnetite has a density of over 5 g/cm^3, and the grain size of primary magnetite is larger than chromite, magnetite may sink the most rapidly in a melt with crystals of multiple minerals
- However, mass-balance could be an issue again if we deal with 60-m-thick oxide layers as in the Panzhihua - Will require an overlying column of 2.5 km of magma (Yao et al. 2001)

Natural Resources Canada Ressources naturelles Canada

Cawthorn et al. 2005 – Econ Geol 100th Ann. Vol

Canada

Crystal Settling, Sorting and Pl Buoyancy



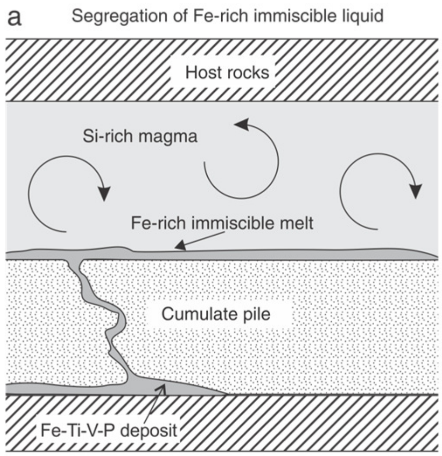
Densities difference after crystallization result in flotation of plagioclase but sinking of the dense Fe–Ti oxides (pilmenite = 4.7, pmagnetite = 5.2).

Plagioclase can float vertically and form anorthosite that is hard to distinguish from the host anorthosite

Plagioclase be transported laterally to form leucocratic rocks in other parts of the magma chamber

Modified Charlier et al. 2015 - ESR

Immiscibility I.



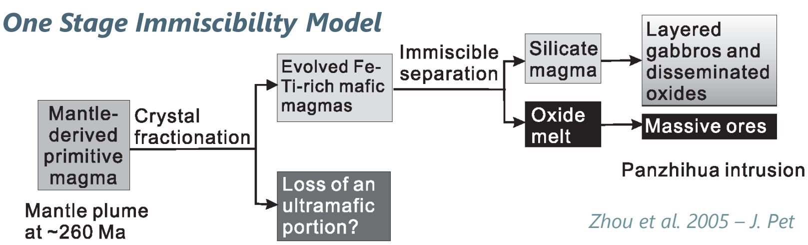
- *Liquid immiscibility is a commonly proposed model for the development of significant massive oxide accumulation*
- *Experimental studies using evolved basaltic compositions have produced immiscible liquids, one Fe rich and the other silica richrich (Naslund 1983; Philpotts and Doyle 1983)*
- *However, in no case did the experimentally produced immiscible liquid contain more than 35 wt.% FeO and still contained considerable normative silicate minerals, not 100% oxide liquid!*
- *It has been also argued that if such Fe-oxide liquid were form, it would percolate into interstitial spaces in the underlying cumulate rather than form planar layer with sharp basal contacts (Cawthorn and Ashwal 2009)*

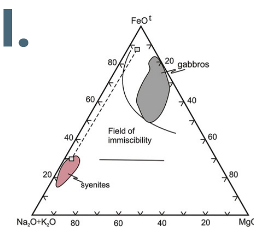
- *Alternatively, immiscibility between Fe-rich and Fe-poor silicate liquids has been identified in the Skaergaard and the Sept Iles intrusions based on the presence of contrasting Fe-rich and Si-rich melt inclusions in apatite and olivine in the upper parts of their stratigraphy (Jakobseen et al. 2005, Charlier et al. 2011, Namur et al. 2012)*

After Charlier et al. 2015; Cawthorn et al. 2005

Genesis of Fe-Ti-V - Panzhihua intrusion II.

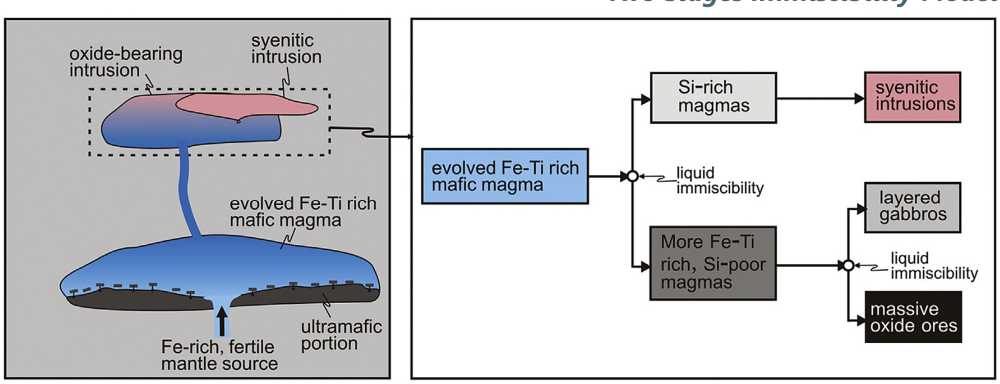
One Stage Immiscibility Model





Zhou et al. 2005 – J. Pet

Two Stages Immiscibility Model



Zhou et al. 2013 – Geo Frontier

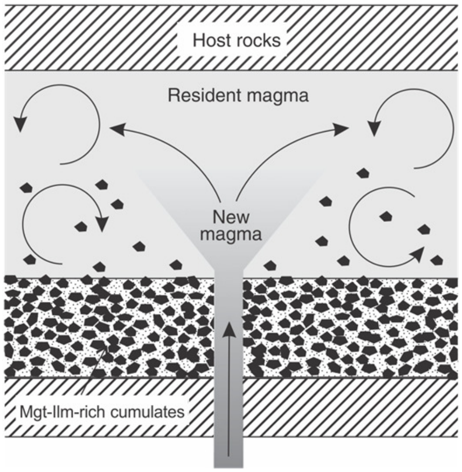
Ore-Forming Processes - Fe-Ti-V-(P) Deposits

Change in physical parameters such as Oxygen fugacity and Pressure

- *An increase in oxygen fugacity (Ulmer, 1969) or total pressure (Cawthorn and McCarthy, 1980) will cause an increase in the magnetite stability field relative to silicate phases, but the source of oxygen, or the driving force for such pressure changes, remains to be identified.*
- *Oxidized conditions promoting magnetite crystallization*
- *Sources for the introduction of fO2 into the system have been proposed including CO2 degassing of footwall rocks (Howarth et al. 2013) and volatile diffusion from underlying cumulates (Klemm 1985)*
- *Although a change in fO2 can account for a change in crystallizing mineralogy but lateral continuity of the magnetitite layers necessitates oxygen to be introduced instantaneously and homogeneously, over a long distance…*
- *A fluctuation in pressure may result in a uniform pressure change simultaneously across the entire strike length. Several mechanisms to change the pressure including magma addition to the chamber and tectonics have been suggested (Cameron 1978; Cawthorn and McCarthy 1981).*

Magma Mixing

Magma mixing that produces a hybrid melt saturated in ilmenite

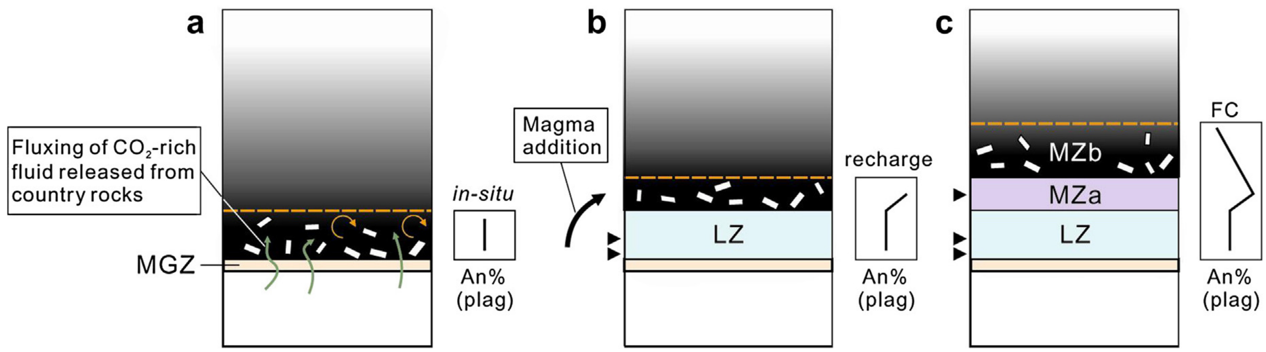


- *Introduction of primitive magma may drive the composition of the resultant magma into the spinel stability field where spinel only will crystallize without other minerals thus resulting in monomineralic layer*
- *Has only been experimentally shown to be plausible for the crystallization of chromitite layers, this* ***process may also apply*** *to magnetitite layers* ***if the addition of new magma will result in magnetite saturation***
- *As example, reversals in plagioclase composition have been documented in the UZ (suggesting magma addition), however, are never coincident with the stratigraphic position of magnetitite layers (Ashwal et al. 2005; Tegner et al. 2006; Cawthorn and Ashwal 2009)*

After Cawthorn et al. 2005; Charlier et al. 2015

45

Contamination-Magma Addition-Fractionation

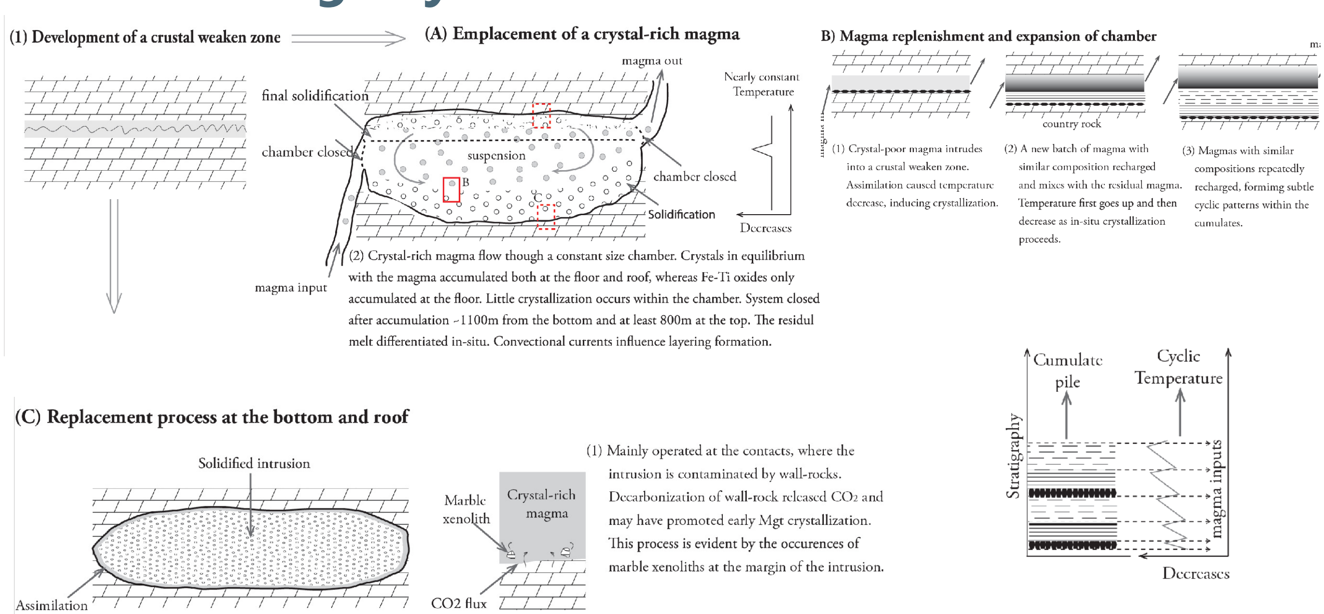


a) *In-situ stage involving fluxing of CO2-rich fluid from the carbonate country rocks and formation of abundant Fe-Ti oxide ores in a relatively dynamic environment (black triangles).*
b) *Recharge stage involving successive addition of magma batches after partial solidification of the LZ and formation of less extensive oxide ore horizons in a relatively static environment; igneous layering is well-developed starting from this stage*
c) *Fractionation stage involving largely closed system fractional crystallization and formation of layered gabbros and leucogabbros in the upper MZa and MZb; ore formation is less favorable at this stage and the Fe-Ti oxides are disseminated in the gabbros.*

Pang et al. 2013 – Geo Frontier

46

Flow Through System Model



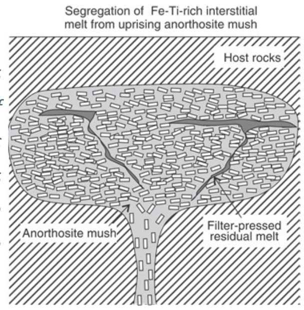
Natural Resources Canada | Ressources naturelles Canada

Guan 2014 – Ph.D Thesis

47

Mobilization and Remobilization

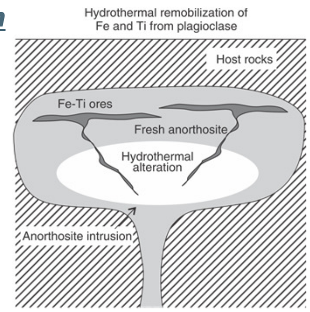
Filter-press compaction



Anorthosite are emplaced as diapirs and crystallize during the ascent of the plagioclase mush. This dynamic emplacement provides the conditions necessary to produce stress-driven melt segregation in partially molten rocks.

Fe–Ti–P-rich rocks formed by segregation of Fe–Ti-enriched residual melts from uprising pure anorthosite mush (commonly >95%plagioclase).

Hydrothermal remobilization



Plagioclase in anorthosite massifs is commonly altered to various degrees and significant volumes of anorthosite can be affected. Li et al. (2014), who show that alteration of plagioclase reduces the Fe and Ti contents of the anorthosite.

They thus interpret the formation of high-grade Fe–Ti–P ores as a hydrothermal process involving P- and F-rich fluids that migrate, alter the anorthosite and transport Fe and Ti.

Solid-state remobilization

It is not rare to observe veins or seams of pure hemo-ilmenite in massif-type anorthosites. However, their emplacement as a melt is highly questionable because the melting point of hemo-ilmenite (at least 1365 ° C, depends on dissolved hematite in the solid solution) is hotter than typical magmatic temperature. Ilmenite can easily recrystallize and migrate by diffusion in subsolidus conditions. It can be inferred that such a migration process also occurs on a larger scale during high-temperature deformation (Duchesne1999).

After Charlier et al. 2015 - ESR

48

Concluding Remarks for Fe-Ti-V-(P) Mineralization

Magmatic Fe-Ti-V deposits have formed throughout geological time from a more restricted range of magma types

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

- *An Fe-rich mafic-anorthositic magma must be generated by fractional crystallization of a more primitive mafic magma*
- *The magma must be generated at or brought to upper crustal levels prior to reaching oxide saturation*
- *Magma must mix with other magmas or rocks in a way so as to precipitate much greater amounts of Fe-Ti-V oxides than normal*
- *The oxides must be segregated and concentrated in a form that is suitable for mining (and preserved from erosion and weathering)*

Natural Resources Canada Ressources naturelles Canada

Canada