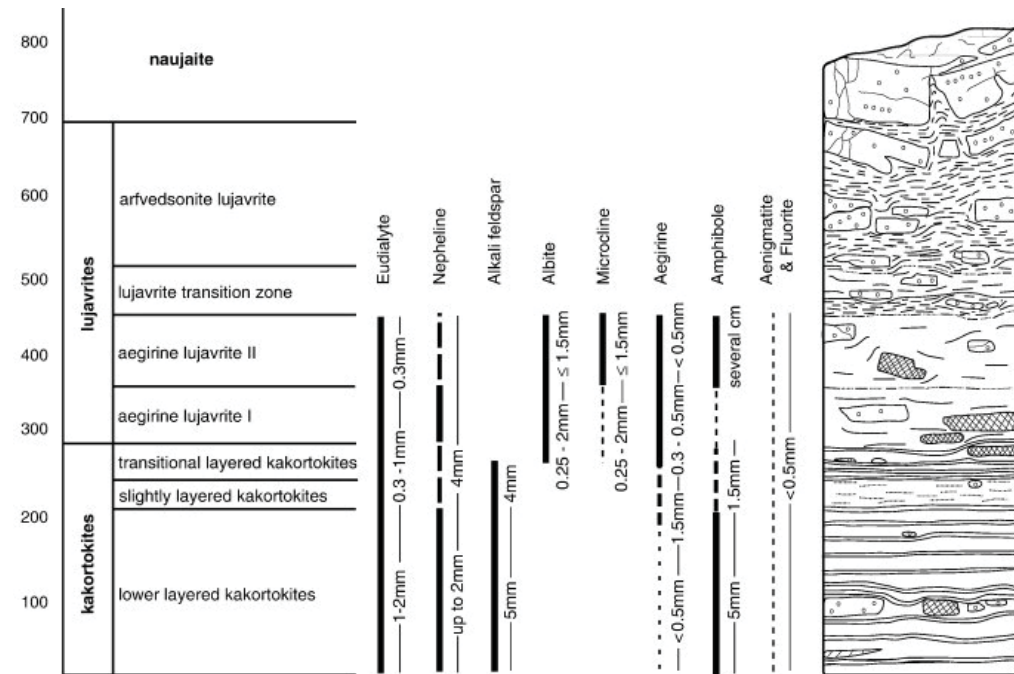
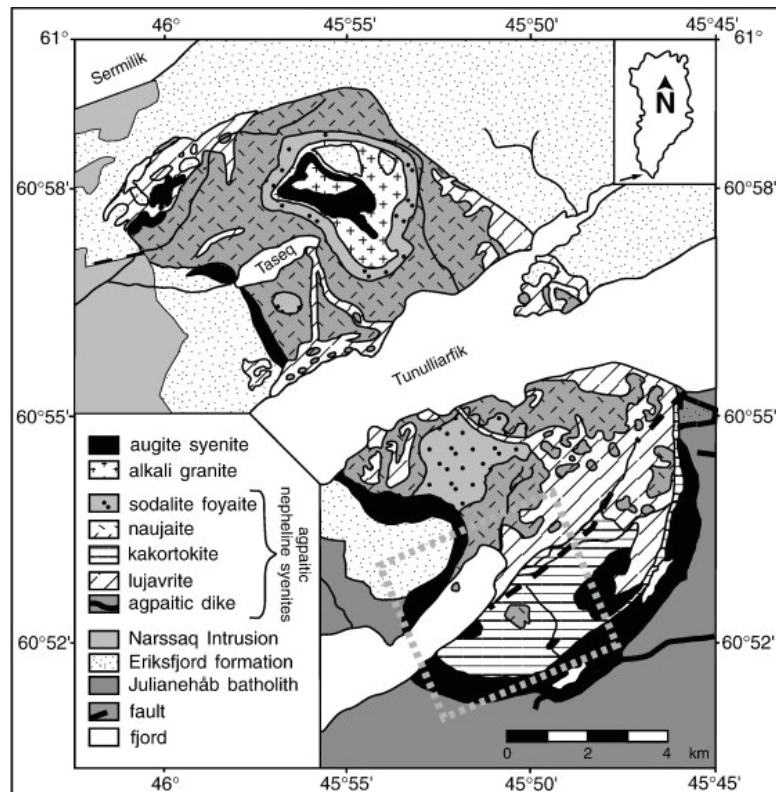


REE mineralization in Illimausac Complex, Greenland

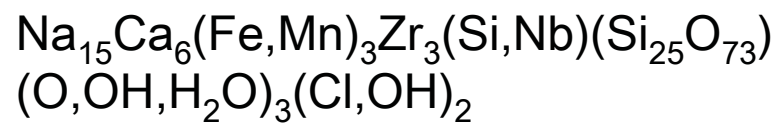


Pfaff et al. (2008)



Mineral	Specific gravity
Albite	2.62
Eudialyte	2.74-3.10
Arfvedsonite	3.30-3.50

Eudialyte:



Chromite in Bushveld complex, SA



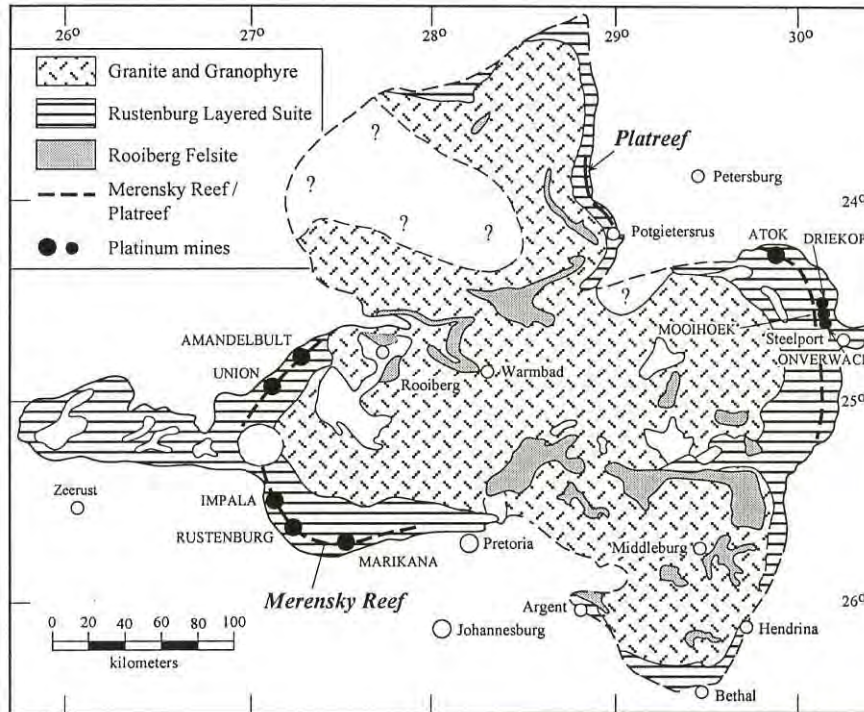
Chromite: Specific gravity 4.5-4.8, Anorthosite: 2.72-2.75

Stratiform Cr deposits

Layered complex	Surface area (km ²)	Age (Ma)	Reserves (Mt)	Estimated sub-economic resources (Mt)
Bushveld, South Africa	67,340	2095+/-24	431	3,910
Great Dike, Zimbabwe	3,265	2461+/-16	64	353
Kemi, Finland	30	2200-2100	33	15
Campo Formoso, Brazil	?	2000?	4	16
Fiskanaesset, Greenland	3,000	Early Archean	?	38
Muskox, Canada	350	1160	?	20
Stillwater, USA	194	2700	?	4
Skaergaard, Greenland	104	52	?	Very thin layer
Mashaba, Zimbabwe	?	2900	?	4

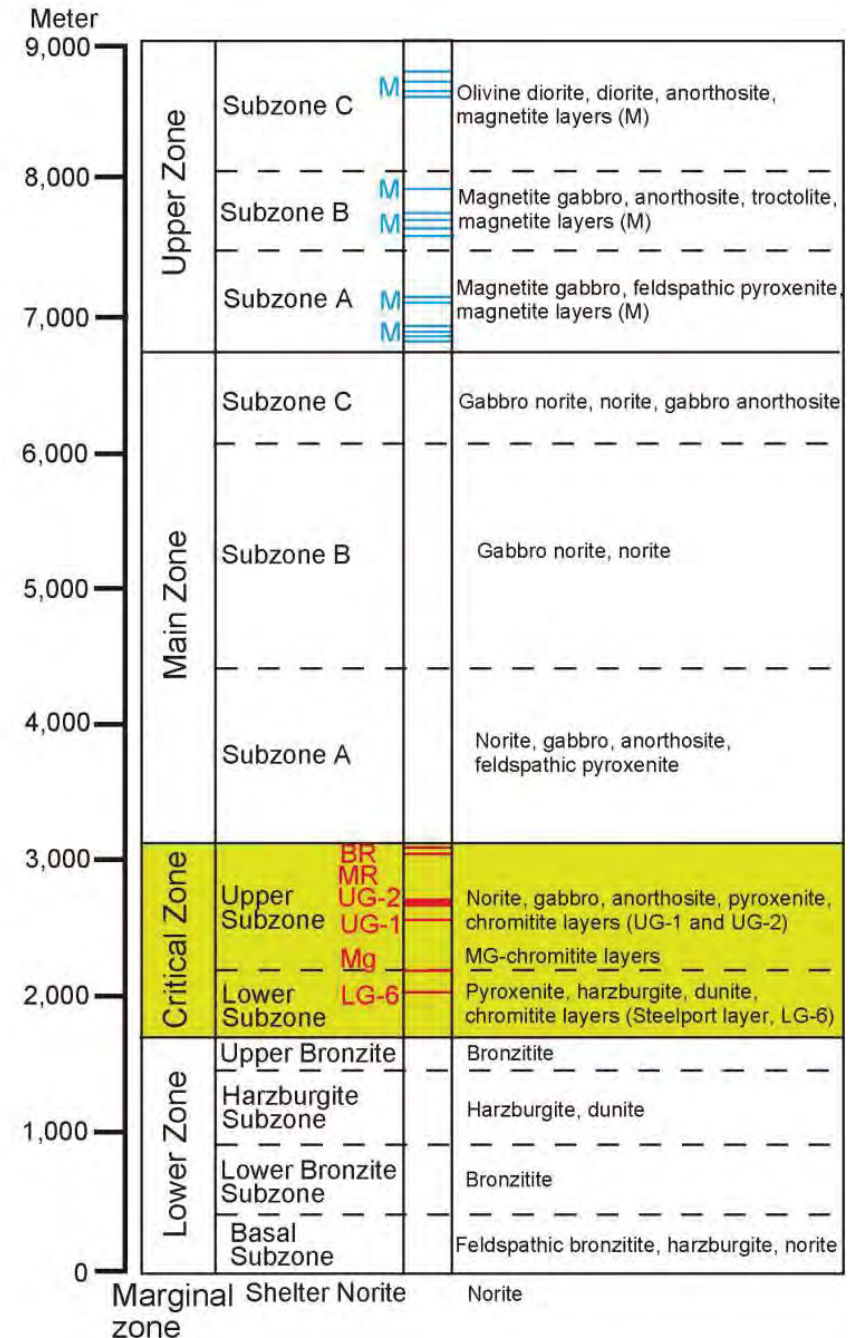
Sources of data: Willemse (1969), Stowe (1987)

Bushveld Cr deposits

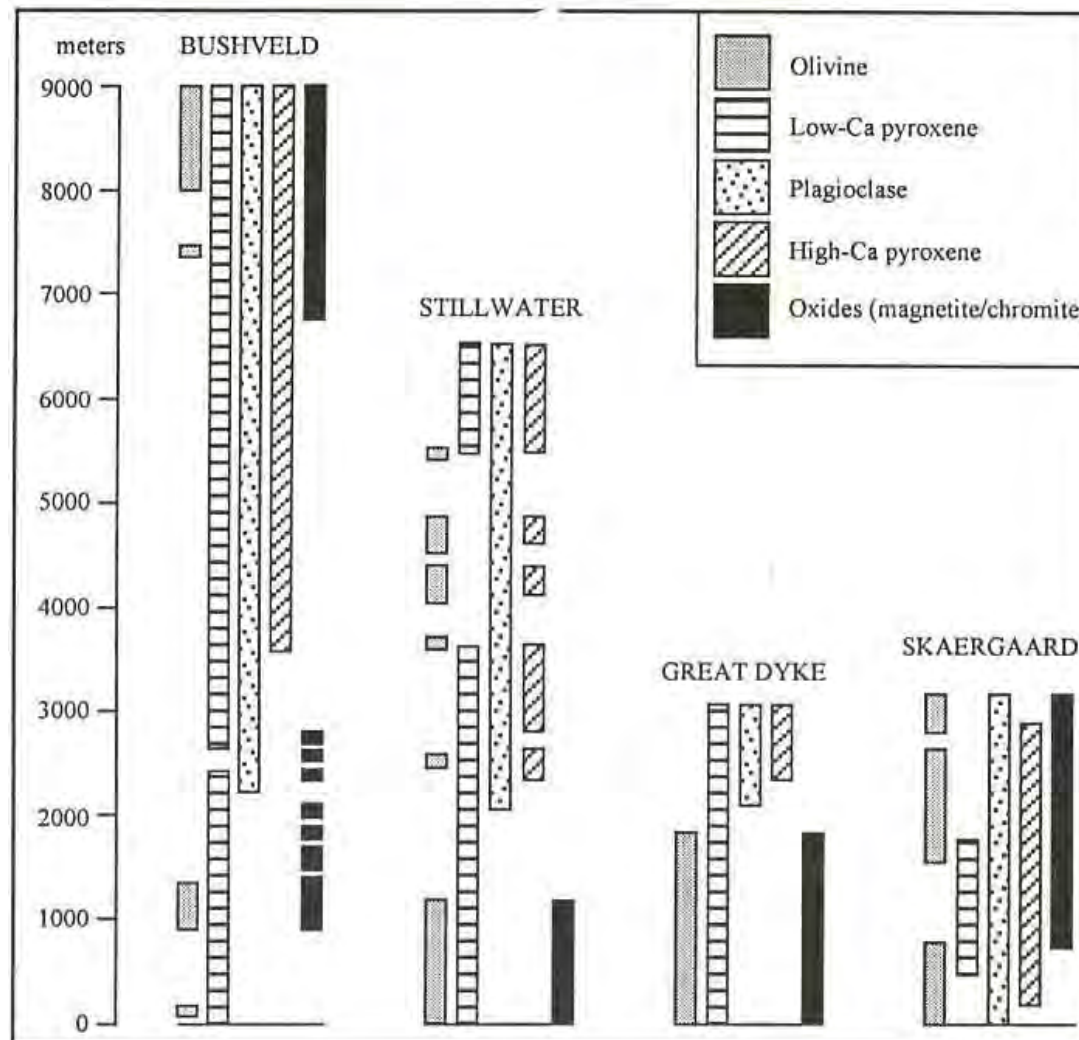


Geological map of Bushveld complex (von Gruenewaldt, 1977, McLaren and De Villiers, 1982)

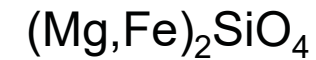
Lithostratigraphic column of the Rustenburg Layered Suite (von Gruenewaldt et al., 1985)



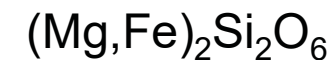
Distribution of cumulus minerals of layered intrusions



Olivine



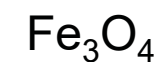
Pyroxene



Plagioclase



Magnetite

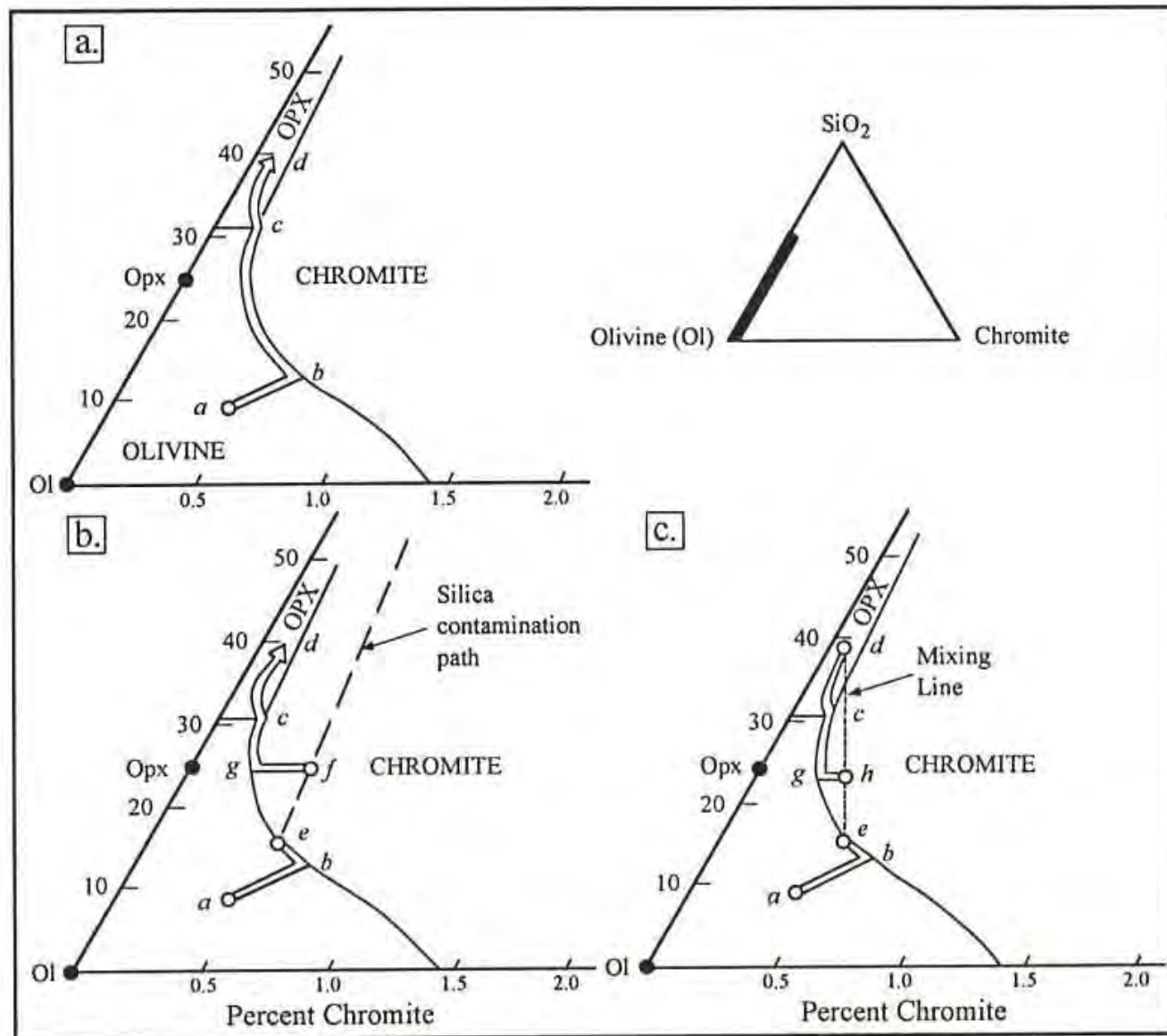


Chromite



Raedeke (1981)

Models for chromite deposition



Irvine (1975)

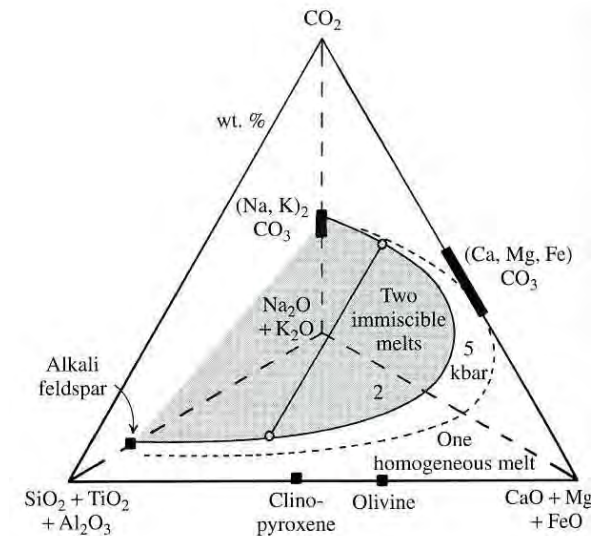
Irvine (1977)

Occurrence of chromite

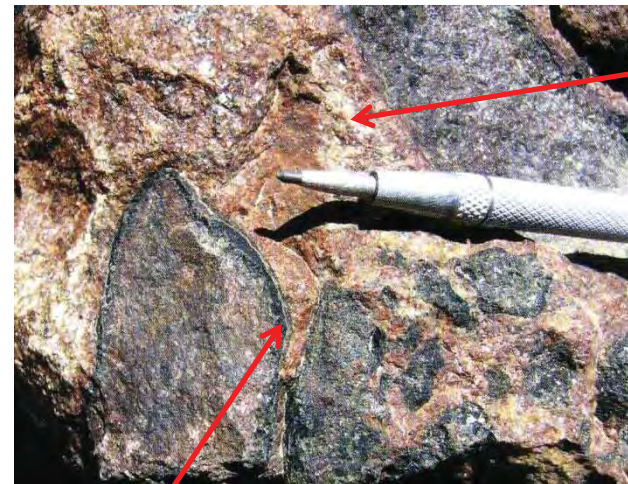


Liquid immiscibility

- Liquid immiscibility is where liquids do not mix with each other.
 - Silicate-silicate
 - Silicate-carbonate
 - Silicate-oxide
 - Silicate-sulfide
- Liquid immiscibility associated with mineralization
 - Ni-Co-PGE deposits
 - Iron oxide, apatite deposits



Best and Christiansen (2001)



Phlogopite $\text{KMg}_3\text{AlSi}_3\text{O}_{10}(\text{OH})_2$

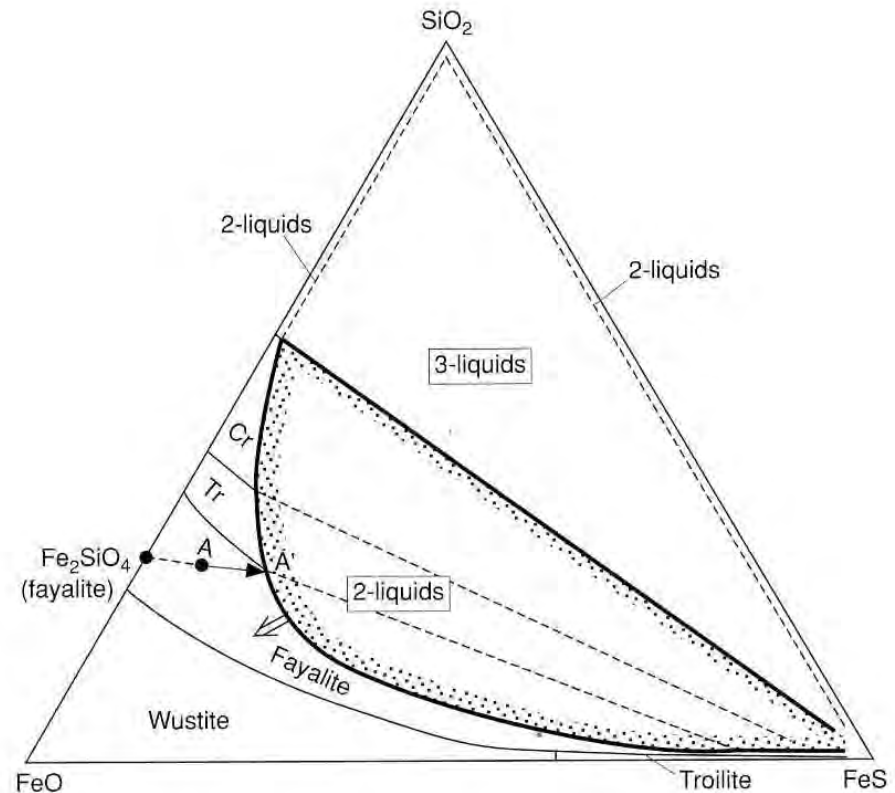
Carbonatite at Mountain Pass, USA

Sulfide mineral segregations

- Sulfide cumulates in layered intrusions are a source of Ni, Cu, PGE and Co. These deposits form by immiscibility between sulfide and silicate melts in a sulfur-saturated magma.
- They are not strictly a cumulate rock, as the sulfide is not precipitated as a solid mineral, but rather as immiscible sulfide liquid. However, they accumulate due to their high specific gravity, and can form laterally extensive sulfide 'reefs'. The sulfide minerals generally form an interstitial matrix to a silicate cumulate.
- Sulfide mineral segregations form when a magma attains **sulfur saturation**. In mafic and ultramafic rocks they form economic Ni, Cu and PGE deposits because these elements are chalcophile and siderophile elements and are partitioned into the sulfide melt.

Immiscibility between silicate and sulfide melts

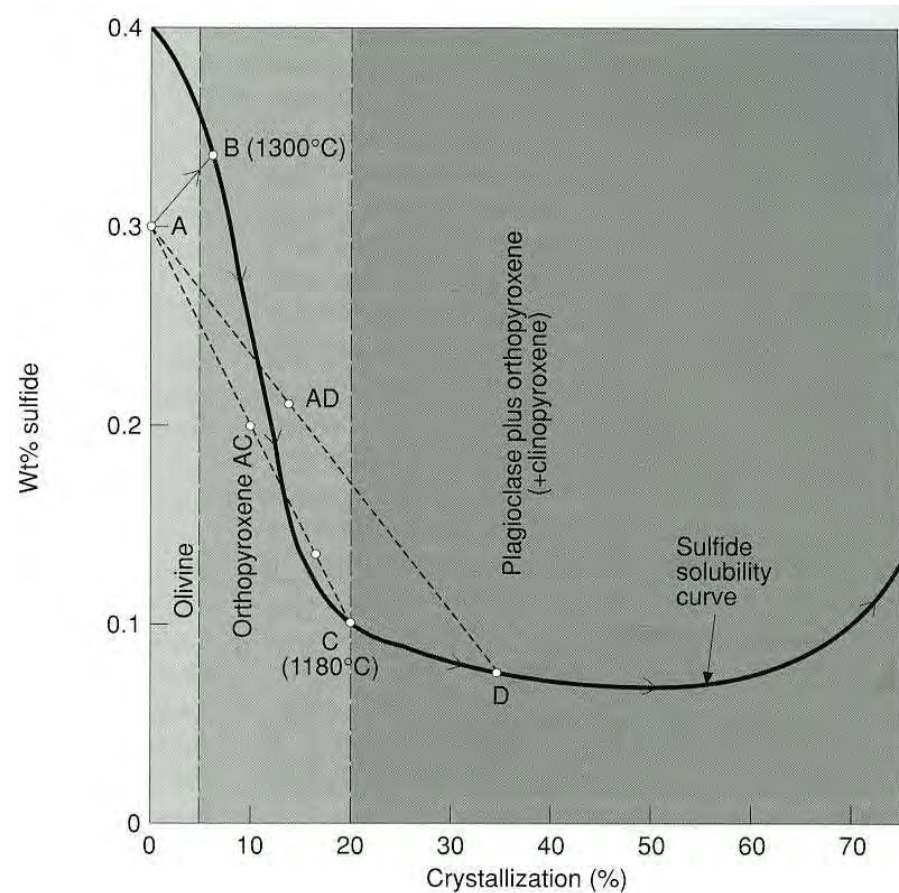
- A melt with A composition changes its composition to A' when Fe olivine (fayalite Fe_2SiO_4) crystallizes.
- The melt with A' composition separates into silicate and sulfide melts.
- When magma is oxidized, immiscible region enlarges towards FeO, resulting in silicate-sulfide separation.



Phase equilibrium diagram of SiO_2 -FeO-FeS system (MacLean, 1969)

Sulfide solubility in magma

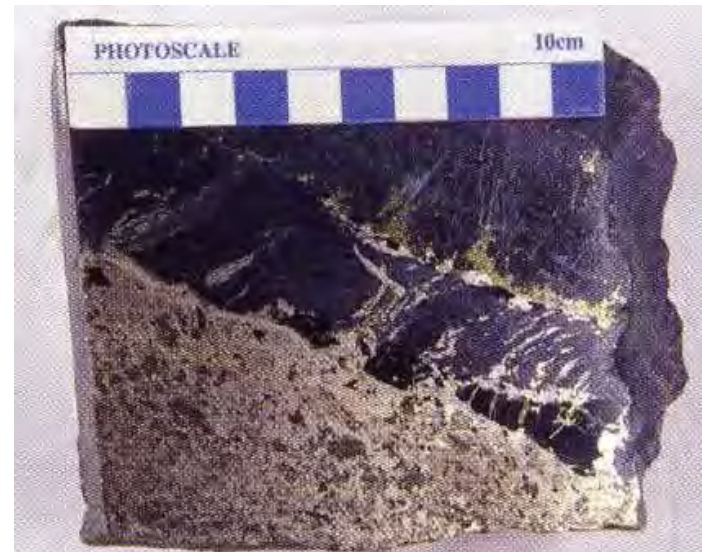
- Solubility of sulfide in magma depends on the amount of oxygen
 - $\text{FeO (melt)} + 1/2\text{S}_2 \rightleftharpoons \text{FeS (melt)} + 1/2\text{O}_2$
- Sulfide solubility increases when the temperature increases, and it decreases when the pressure or SiO_2 content increase.
- Magma mixing triggers sulfide supersaturation.



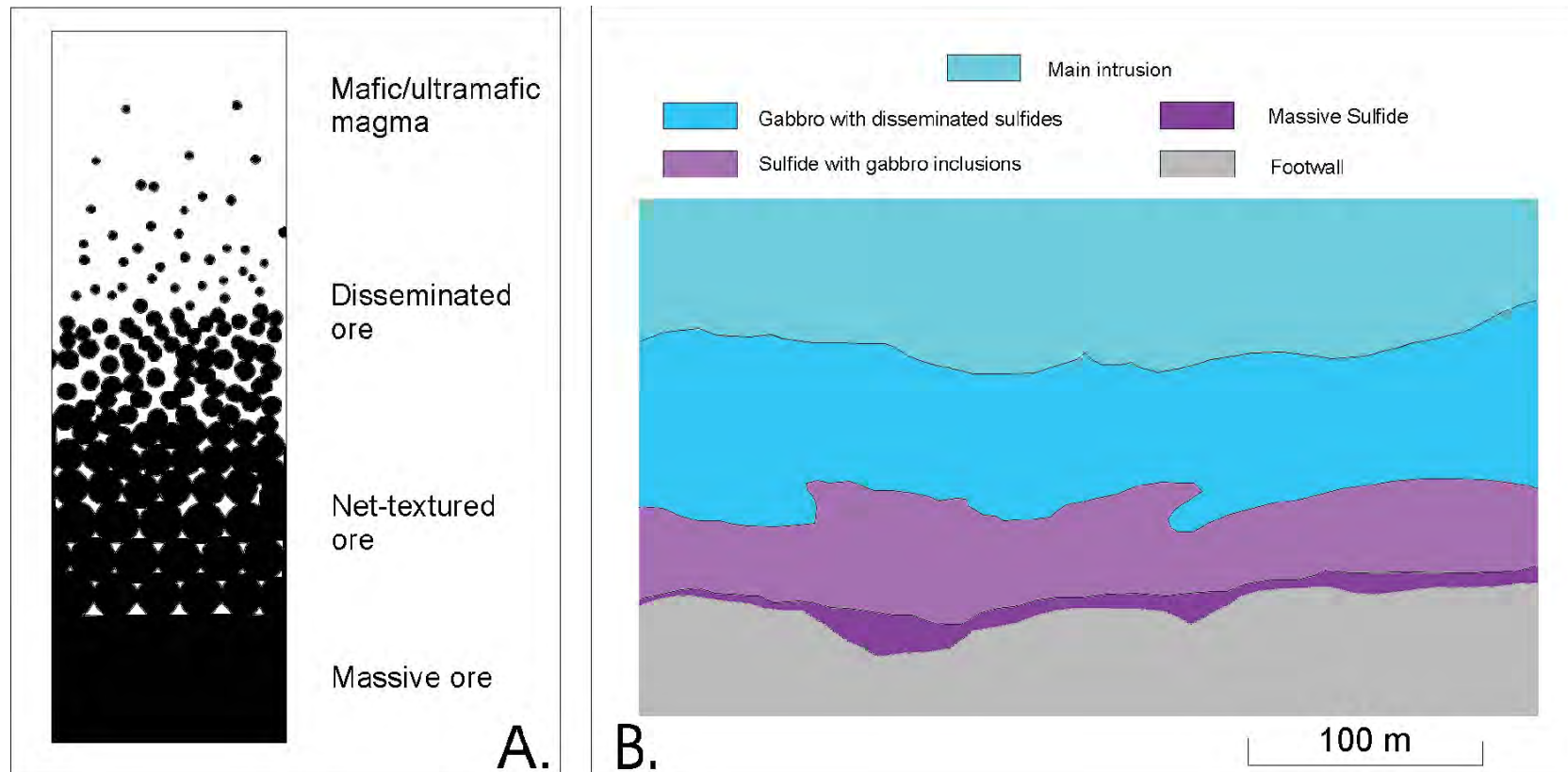
Naldrett & Von Grunewaldt (1989)

Condition for the formation of metal deposits from immiscible sulfide melt

- Abundant formation of immiscible sulfide melt
- Accumulation of sulfide melts into the base of the magma chamber



Model for magmatic sulfide deposits

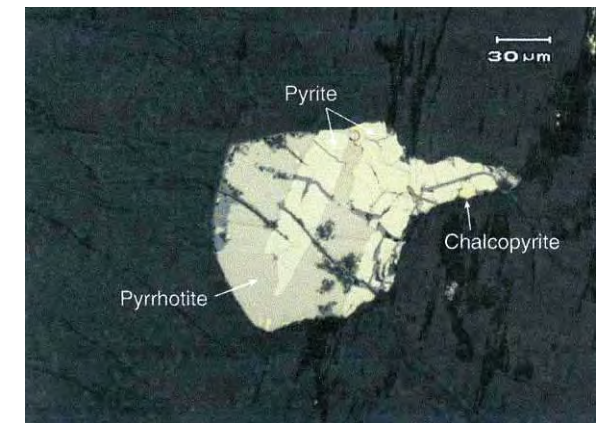
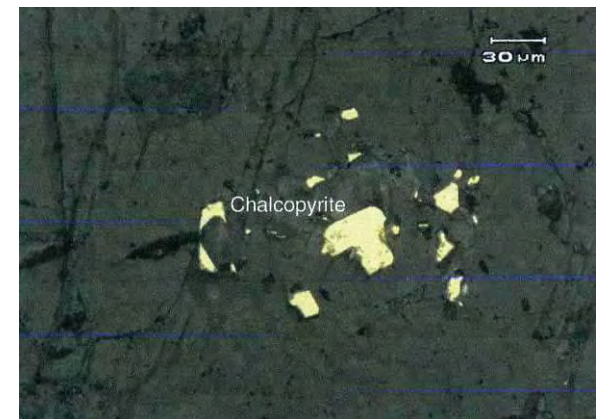


A, Schematic section of a magmatic sulfide deposit showing the vertical gradation downward from disseminated to massive ore. *B*, Generalized map showing massive sulfide mineral concentrations in footwall embayments of the Sudbury Complex, Canada (Foose et al., 1986).

Sulfide-silicate partition coefficients

	Ni	Cu	Co	Pt	Pd
Komatiite					
27% MgO	100	250-3000	40	10^4 - 10^5	10^4 - 10^5
19% MgO	175	250-2000	60	10^4 - 10^5	10^4 - 10^5
Basalt	275	250-2000	80	10^4 - 10^5	10^4 - 10^5

Naldrett (1989), Barnes & Francis (1995),
Tredoux et al. (1995)



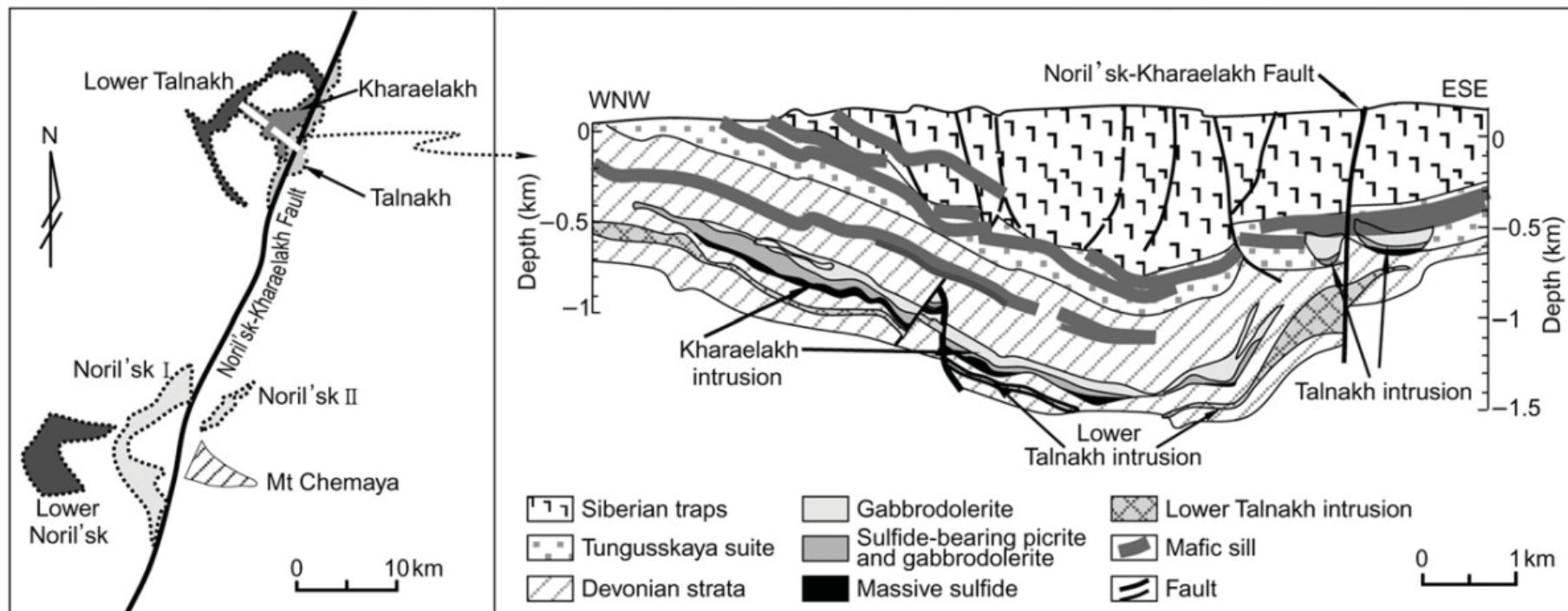
Richards (2011)

Noril'sk Ni-Cu-PGE deposit, Russia

Ore reserves : 2.32Mt@1.77%Ni,

4.67Mt@3.57%Cu,

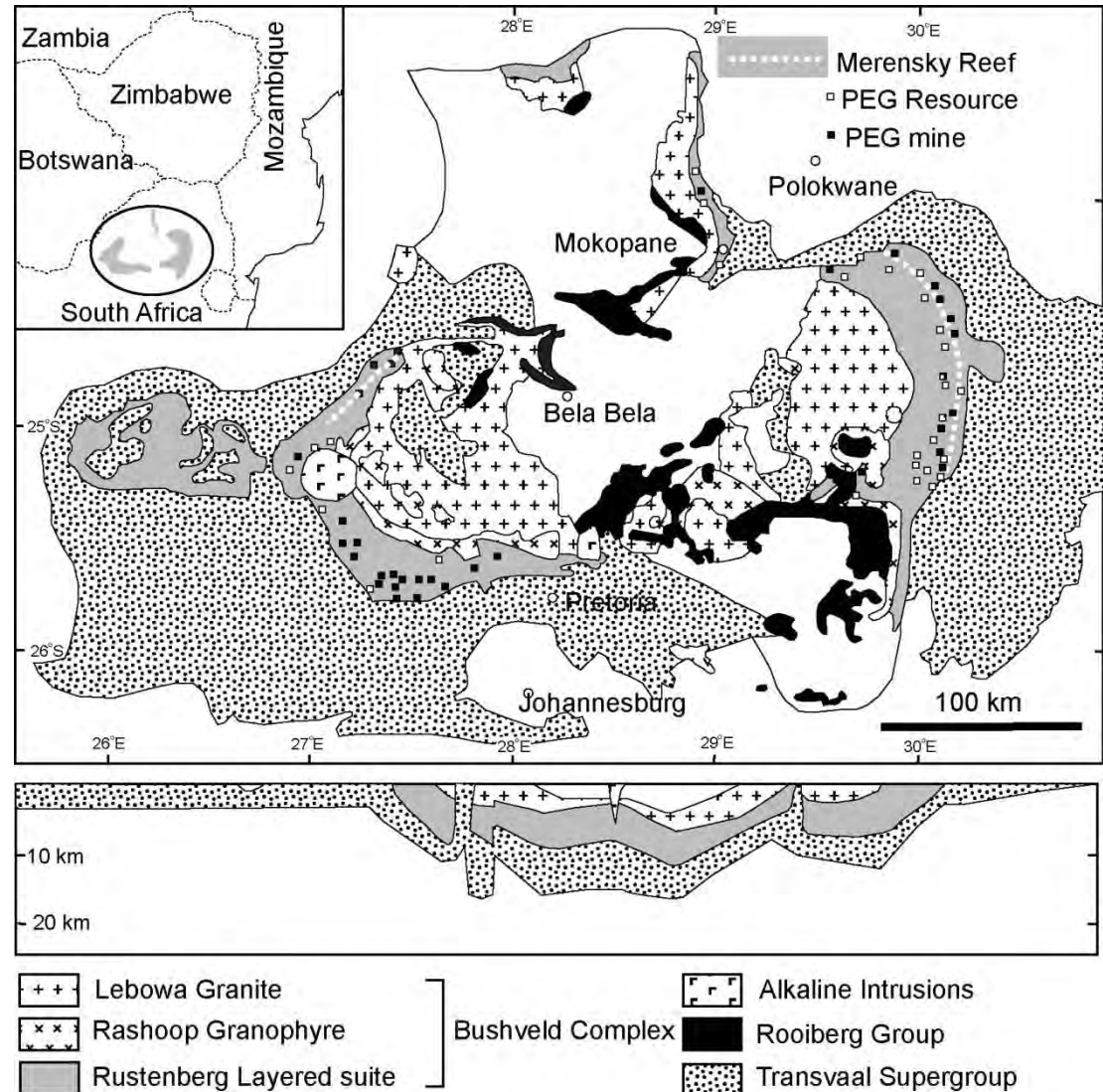
12,438t@9.5ppm Pt



Naldrett (2004)

PGE mineralization in the Bushveld Complex, South Africa

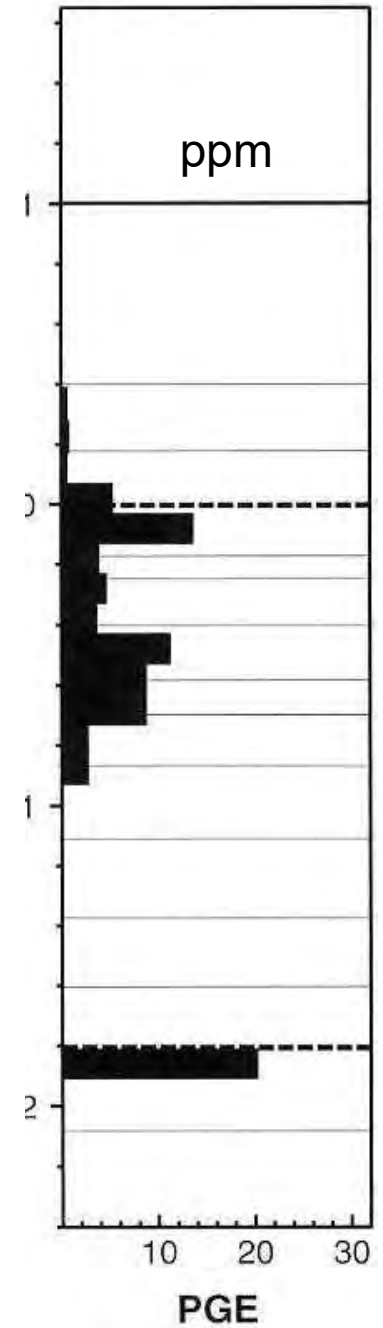
- About 80% of world resources
- Orebody: Merensky Reef, UG2, Platreef
- A few centimeter to a few meter layers extending over a few 100km
- Over 1000 times concentration of PGE compared to the host rock (1.6-6.1ppb)



Merensky Reef



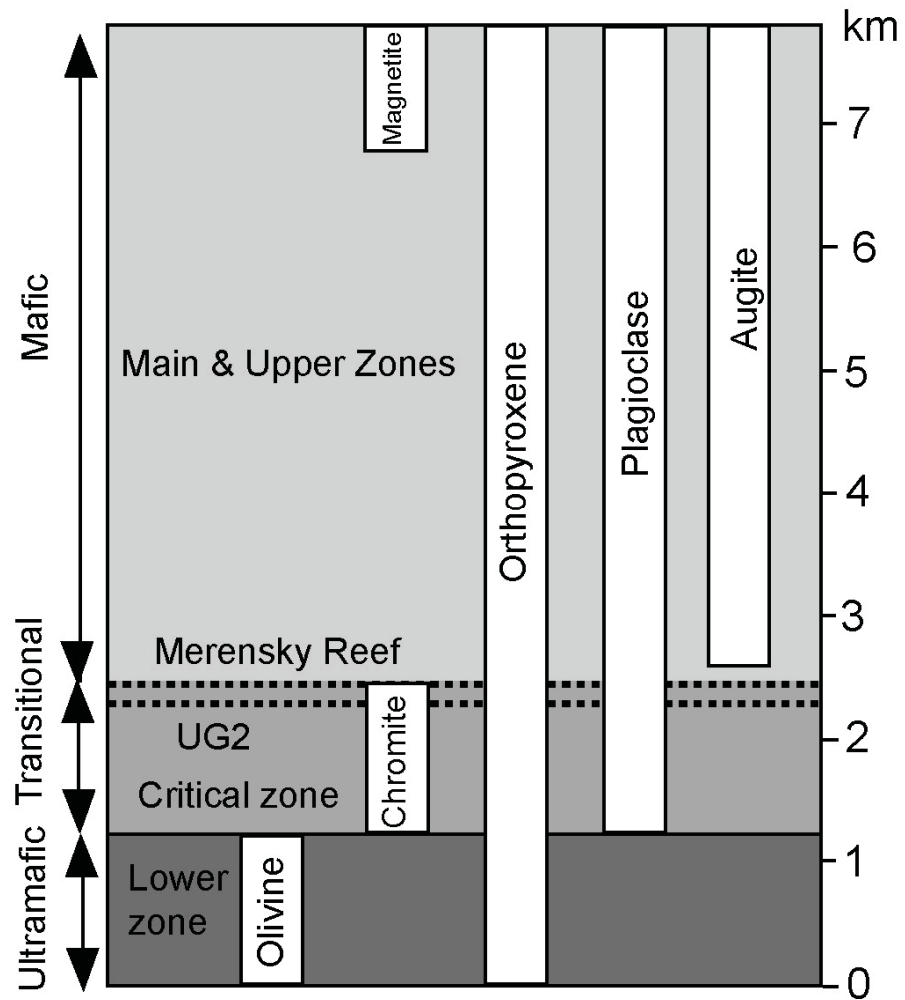
Mitchell & Scoon (2007)



PGE ore from Merensky Reef in the Bushveld complex, South Africa



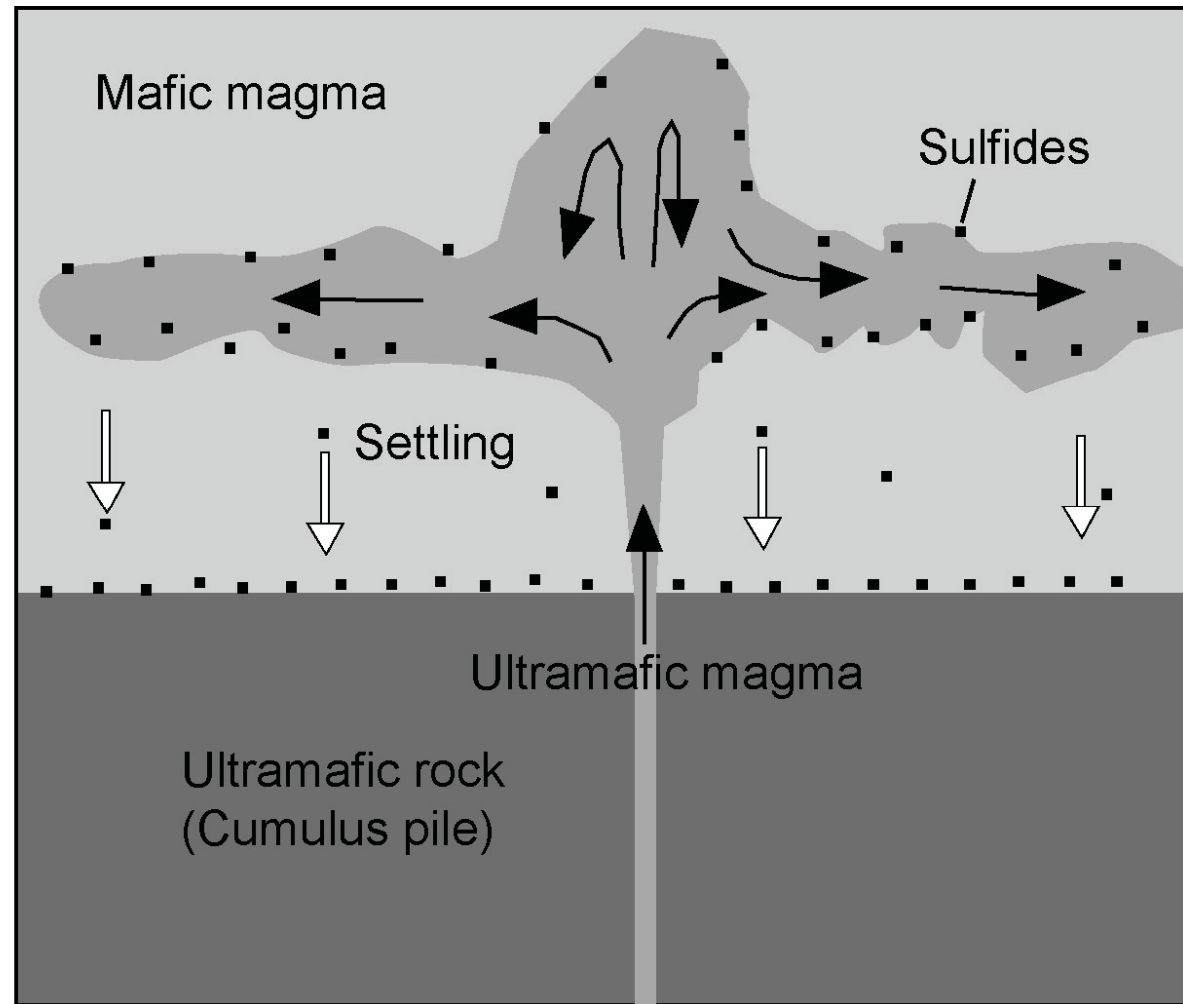
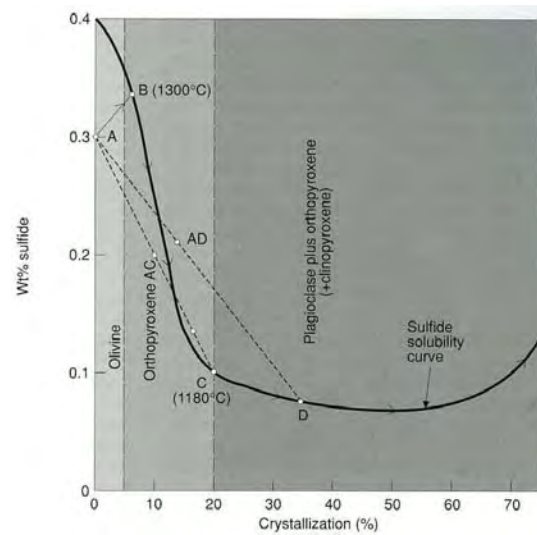
Bushveld Complex



Location of Merensky Reef and UG2 in the Bushveld Complex (Campbell et al., 1983)

Genesis of Merensky Reef

- Magma mixing



Pyroxenite dike in anorthosite



The Waterberg Project

- PTM created concept of “New Business Unit”
- 2007 A Team of 9 academics and industry experts in one room doing target generation.
- 108 Targets were identified.
- Ranking system were used.
 - Size, Depth, Grade, Potential, Location.
 - Waterberg project was ranked in top 10.
 - Possible Placer type deposit. – in sediments.
 - Extension of the current Northern Limb.
 - With a strike change and unexplored under cover.
- Drilling started in July 2010
- WB003 intersected a mineralized zone in October 2011 (T Zone)



PTM Targets
Ranking and Geological Description

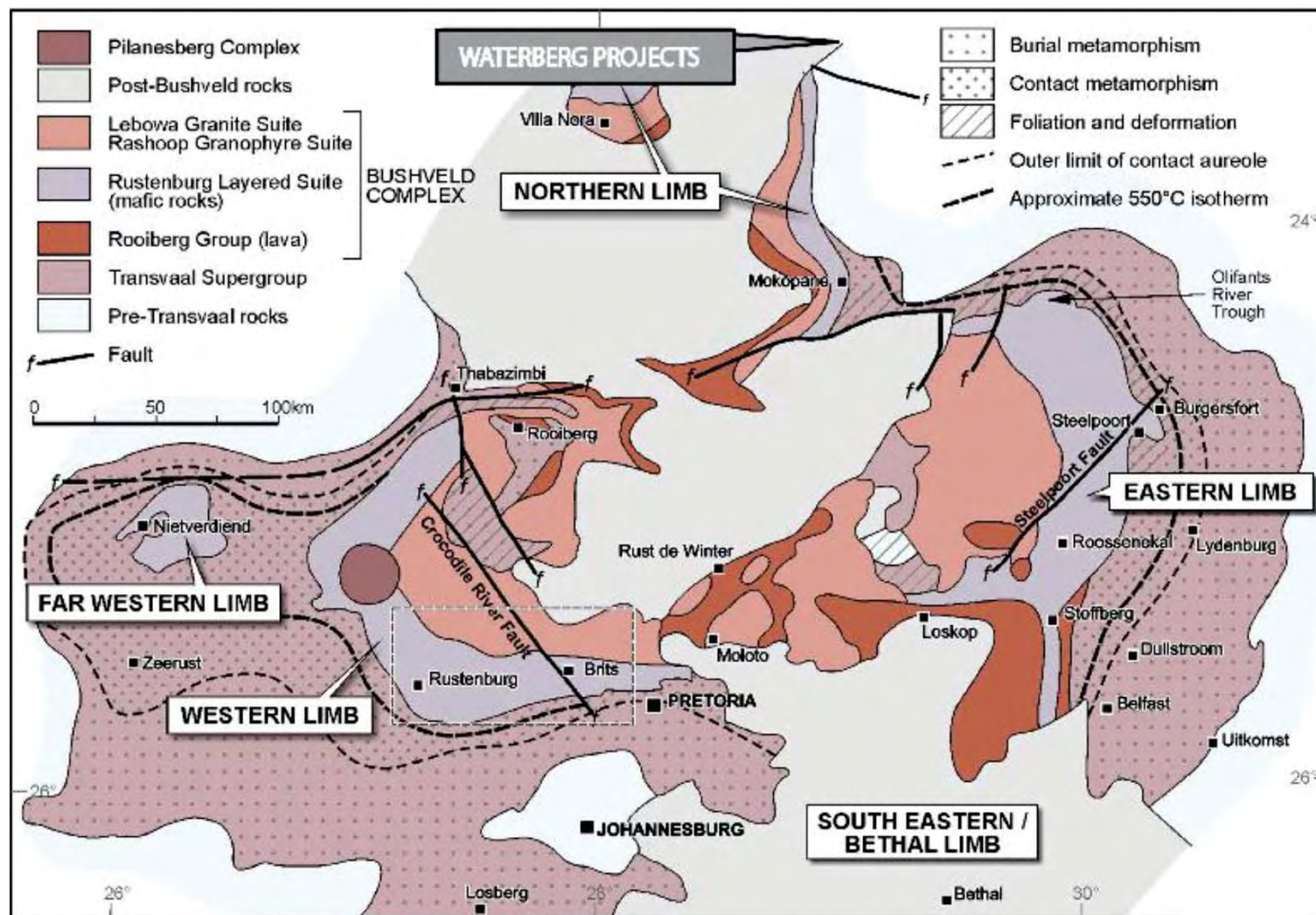
Requested By: Mr Willie Visser
Mr John Gould
PTM

Contributors: Prof Sybrand de Waal
Prof Spike McCarthy
Mr Harry Meadon
Mr Bernie Green
Mrs Vanessa Vermaak
Mrs Nicky Vloek
Ms Tina Govender
Mr Phil Lambert
Dr Jochen Schwelzer

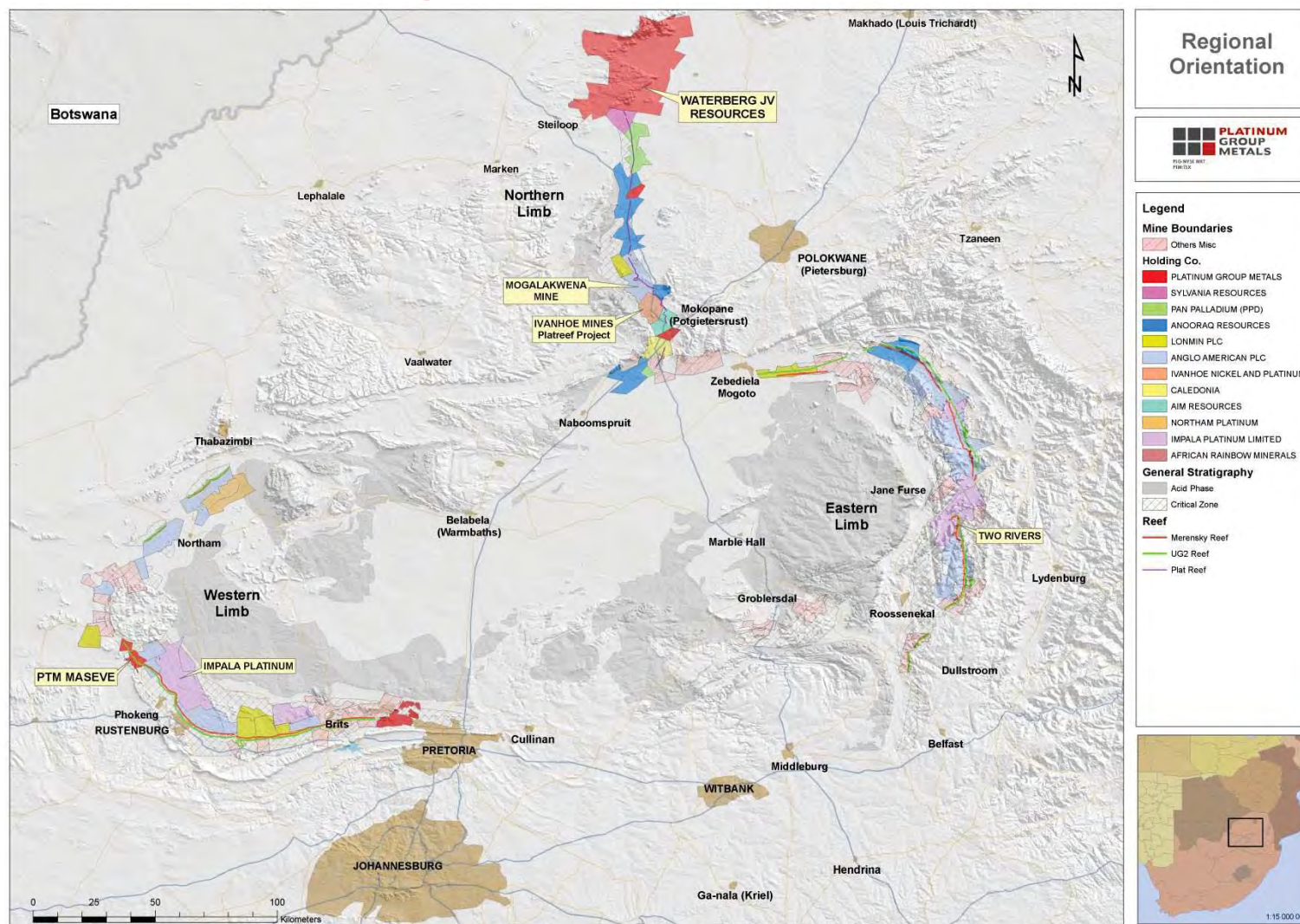
Date: 16 April 2007

Report No: 00103/07-1

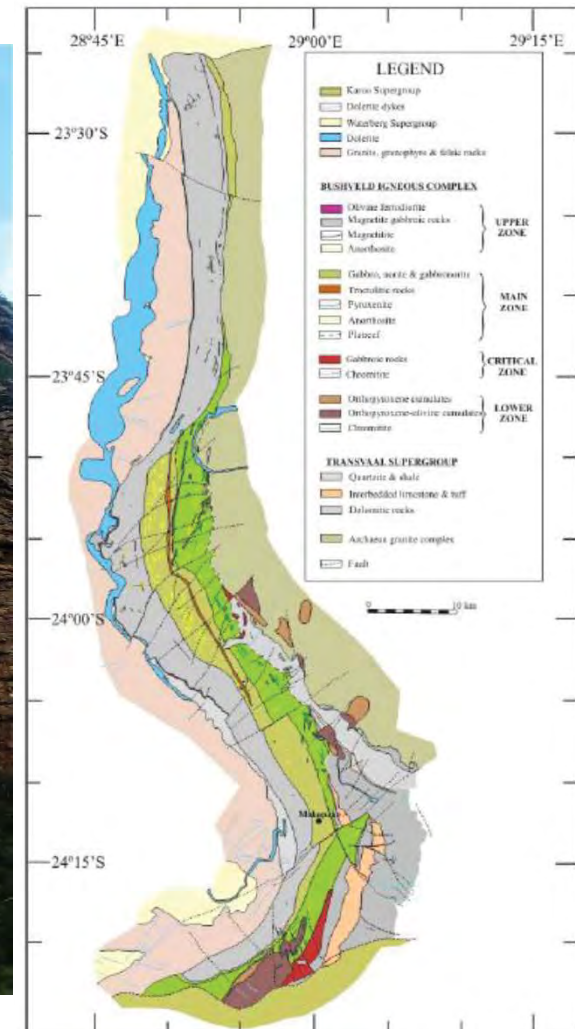
Denroo Trading 198 (PTY) Ltd t/a Sango Solutions
Registration Number: 2004/003805/07
H.M.K. House, C/o Ethel Rd and Ruth Crescent, Northcott
Tel/Fax: +27 (0)11 878 6804



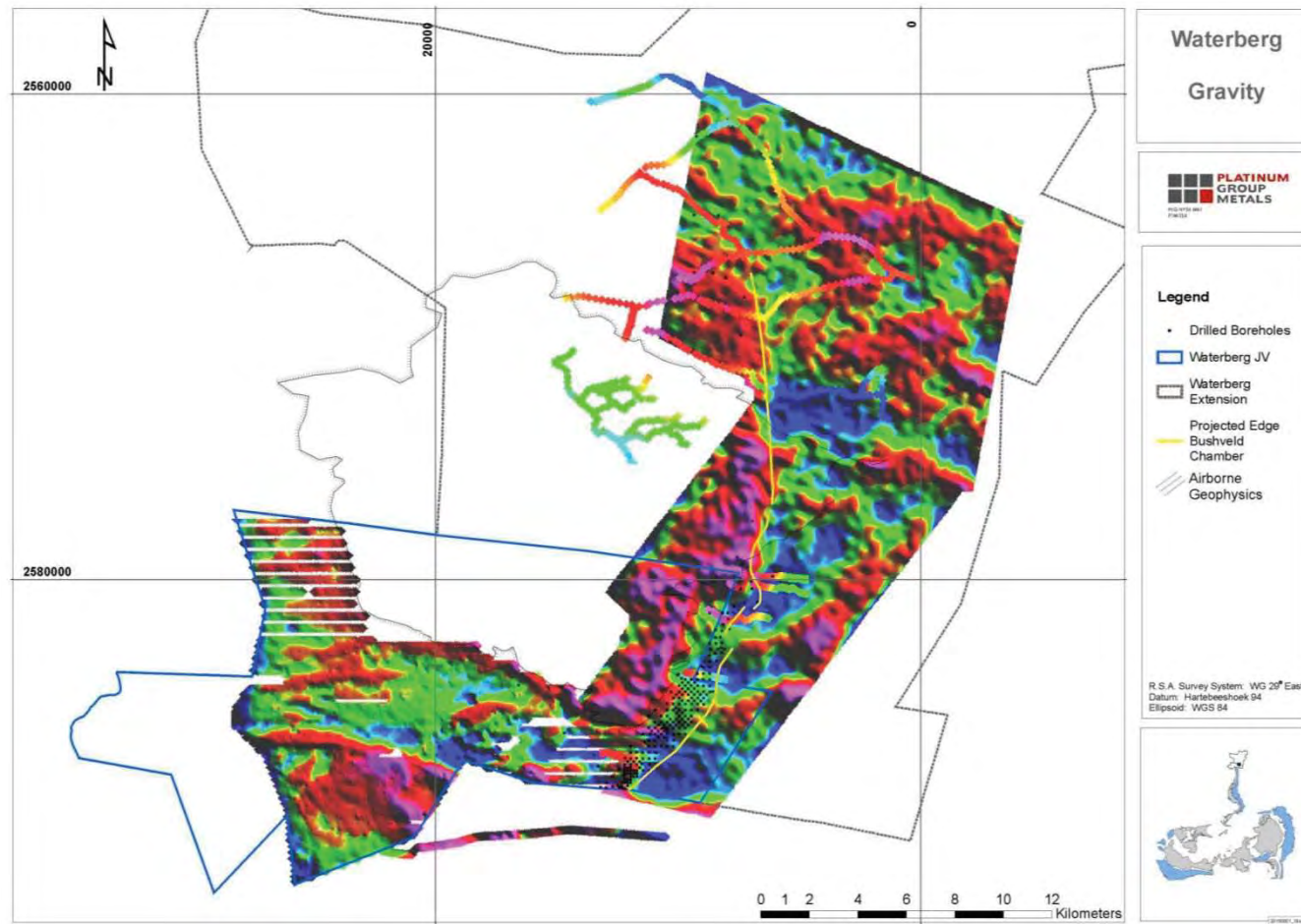
Regional Orientation



Waterberg Formation

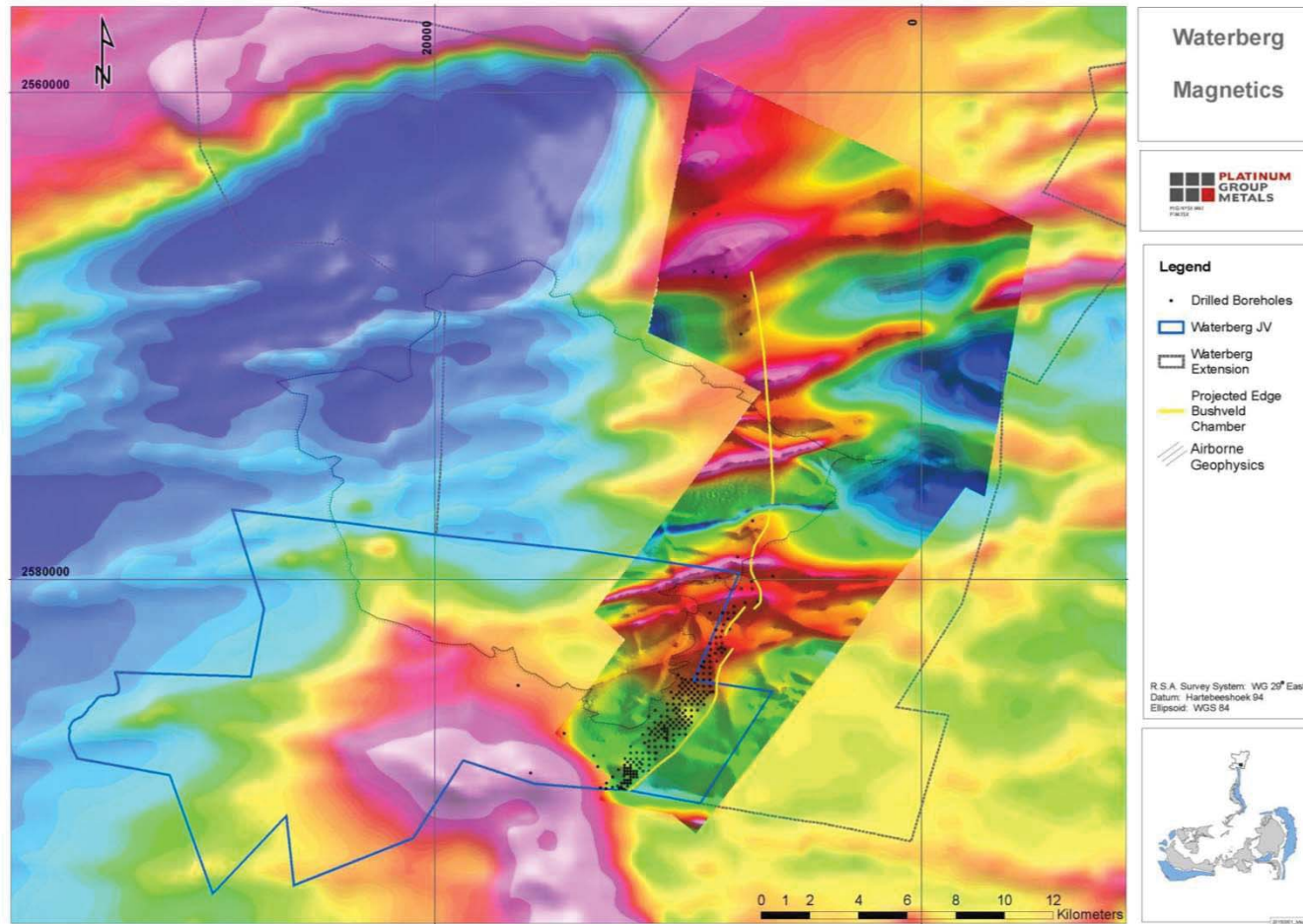


Airborne gravity



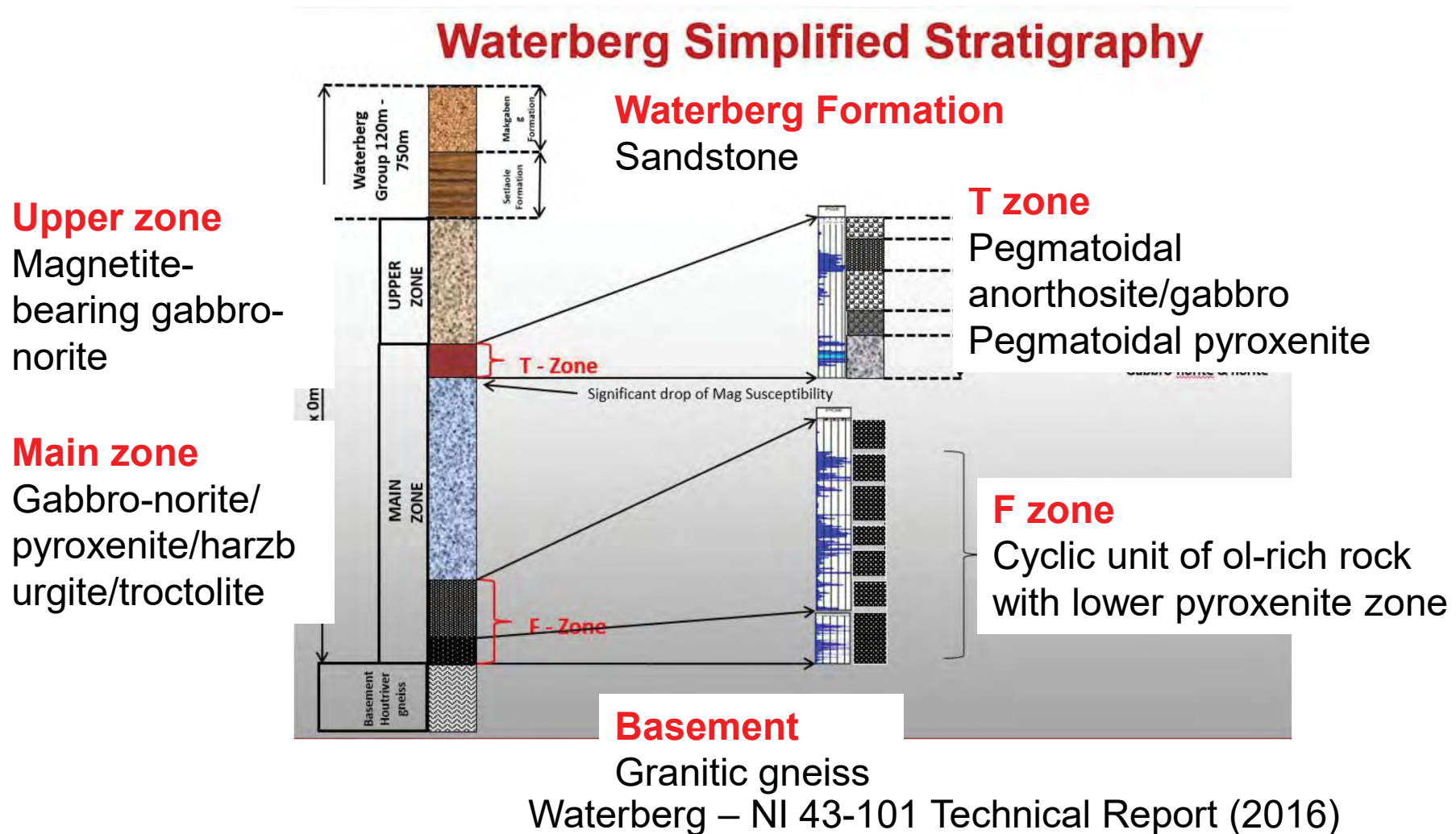
Waterberg – NI 43-101 Technical Report (2016)

Airborne Total Field Magnetics

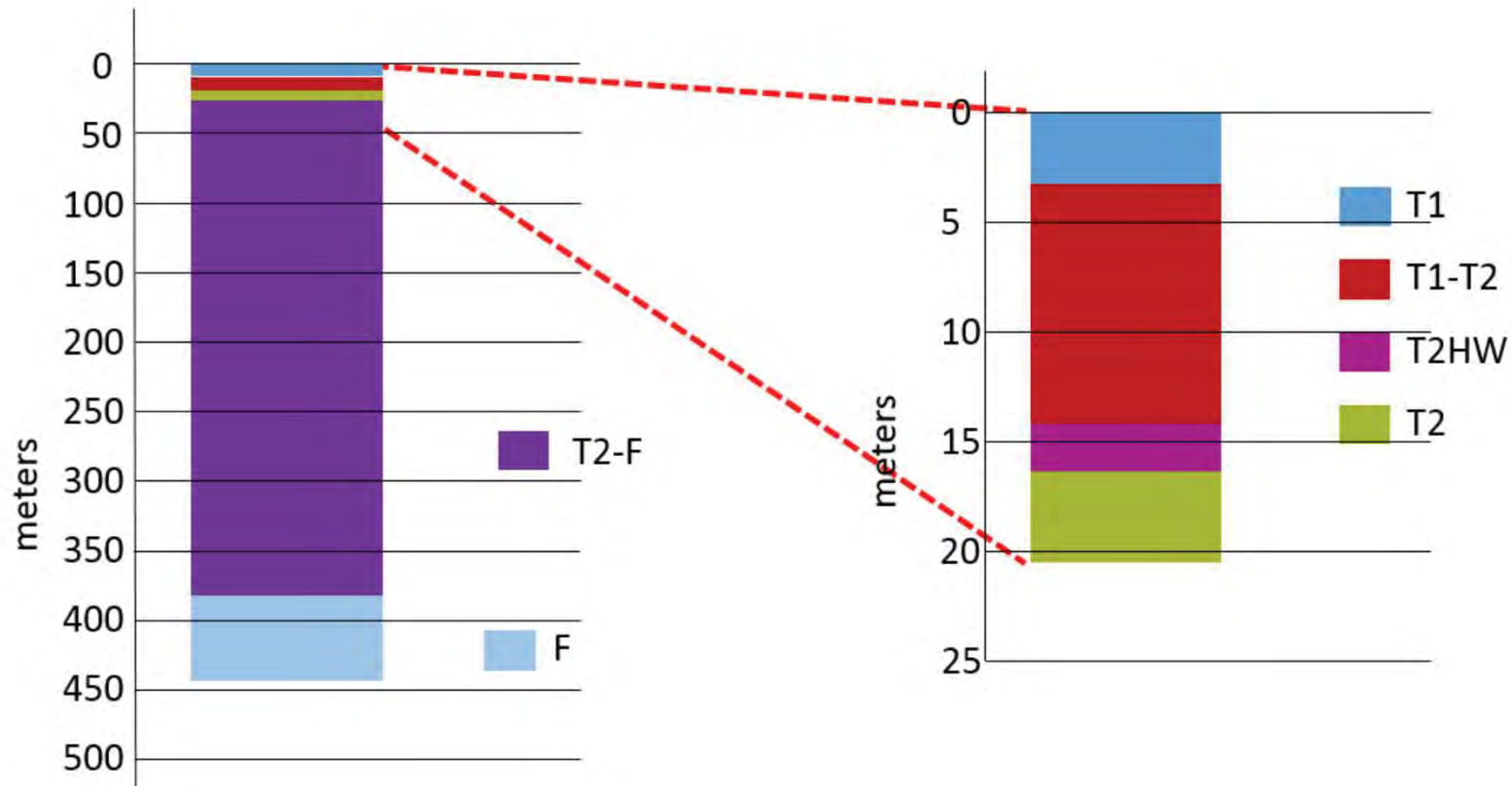


Waterberg – NI 43-101 Technical Report (2016)

Waterberg stratigraphy



Stratigraphy of mineralized layers



T zone

- UPA (Upper Pegmatoidal Anorthosite), T1 hanging wall.
- T1 Layer
 - hosted in troctolite with variations in places where troctolite grades into feldspathic harzburgite.
 - Mineralised with blebby to net-textured Cu-Ni sulphides (cp/py and pnt).
- LPA (Lower Pegmatoidal Anorthosite) & LPP (Lower Pegmatoidal Pyroxenite).
- T2 Layer
 - hosted in gabbro/norite with elongated milky feldspars, tends to grade into pyroxenite.

F zone

- Gabbro/norite (100-450m thick) underlies the T-Zone and overlies the F-Zone.
- F-Zone is hosted in a package of troctolite, which has small bands of pyroxenite and harzburgite.

Mineral Resource estimate

Resource Category	Reserve (Mt)	Pt (g/t)	Pd (g/t)	Au (g/t)	Rh (g/t)	4E (g/t)	Cu (%)	Ni (%)	4E (t)
T zone									
Indicated	31.54	1.13	1.90	0.81	0.04	3.88	0.16	0.08	122
inferred	19.92	1.10	1.86	0.80	0.03	3.79	0.16	0.08	75.5
F zone									
Indicated	186.7	1.05	2.23	0.17	0.04	3.49	0.07	0.16	652
inferred	77.30	1.01	2.16	0.17	0.03	3.37	0.04	0.12	261
Total									
Indicated	218	1.06	2.18	0.26	0.04	3.55	0.08	0.15	774
inferred	97	1.03	2.10	0.30	0.03	3.46	0.06	0.11	336

Metal ratio

Prill split					Grade	
Zone	Pt (%)	Pd (%)	Au (%)	Rh (%)	Cu (%)	Ni (%)
T zone	29	49	21	1	0.16	0.08
F zone	30	64	5	1	0.07	0.16

Major gangue mineralogy

Mineral	T2	F
Pyroxene	32.92	30.40
Plagioclase	46.58	16.40
Chlorite	4.54	14.24
Serpentine	1.03	17.08
Talc	3.30	10.34
Olivine	0.22	3.99
Amphibole	2.19	1.48
Quartz	3.05	0.23
Mica	1.89	0.87
Calcite	1.66	1.07
Fe/Ti oxides	0.39	1.41
Apatite	0.21	0.13

Waterberg – NI 43-101 Technical Report (2016)

Major ore mineralogy

Mineral		T2	F
Pentlandite	(Fe,Ni) ₉ S ₈	0.11	0.44
Chalcopyrite	CuFeS ₂	0.33	0.24
Pyrrhotite	Fe _{1-x} S	0.10	0.52
Pyrite	FeS ₂	0.20	0.14
Chromite	FeCr ₂ O ₄	0.05	0.21

Waterberg project



Typical lithofacies



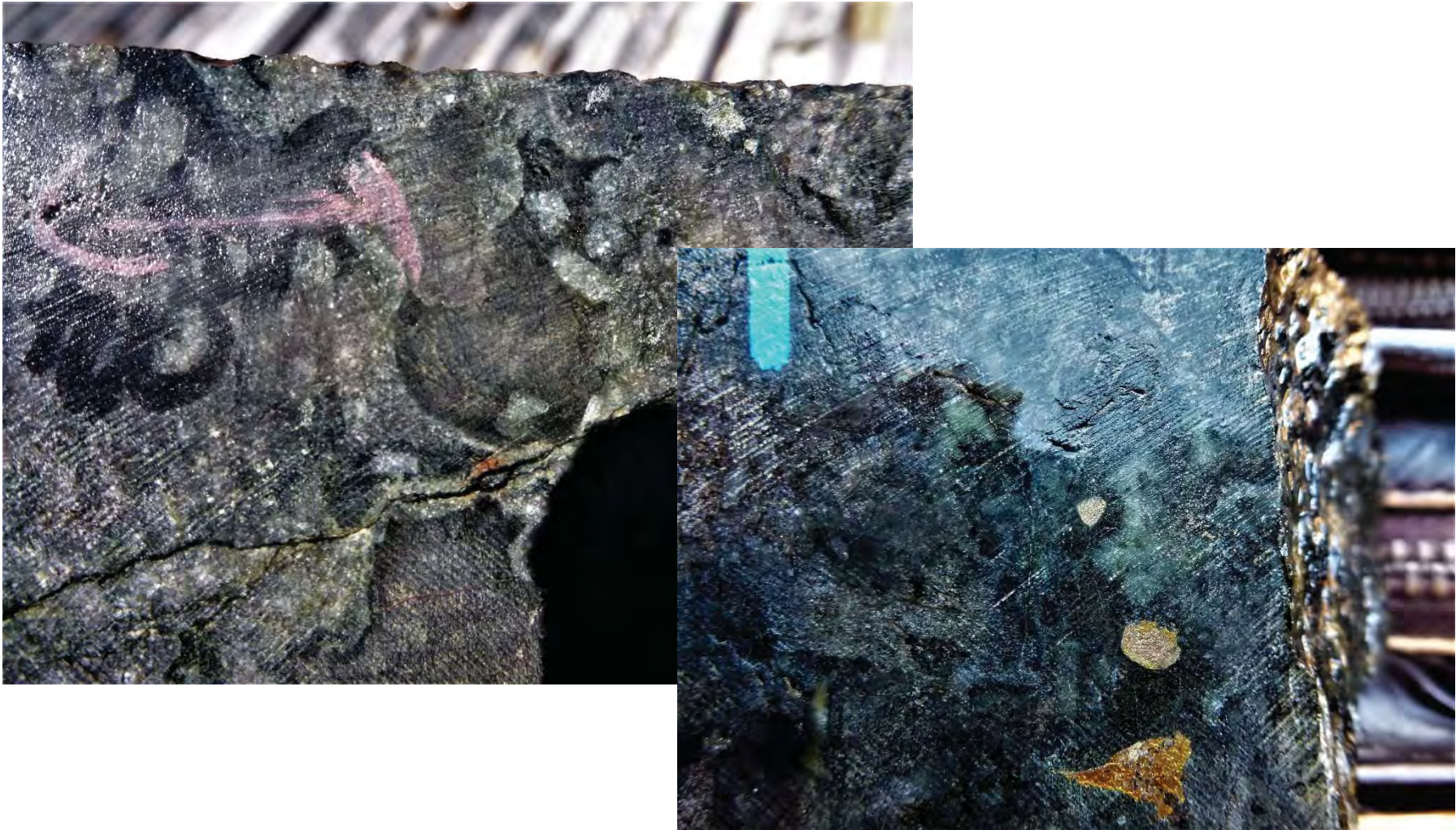
Typical lithofacies



Typical lithofacies



Sulfide mineralization



Sulfide mineralization



Sulfide mineralization



What do we want to study?

- Processes that concentrate sulfides & PGE
 - magma mixing
 - magma fractionation
 - assimilation of sedimentary rocks
 - role of volatiles
- Source of metals & metal ratios
 - Pt:Pd, Au, Ni, Cu, Te, Bi, As
- Why no chromium?

