



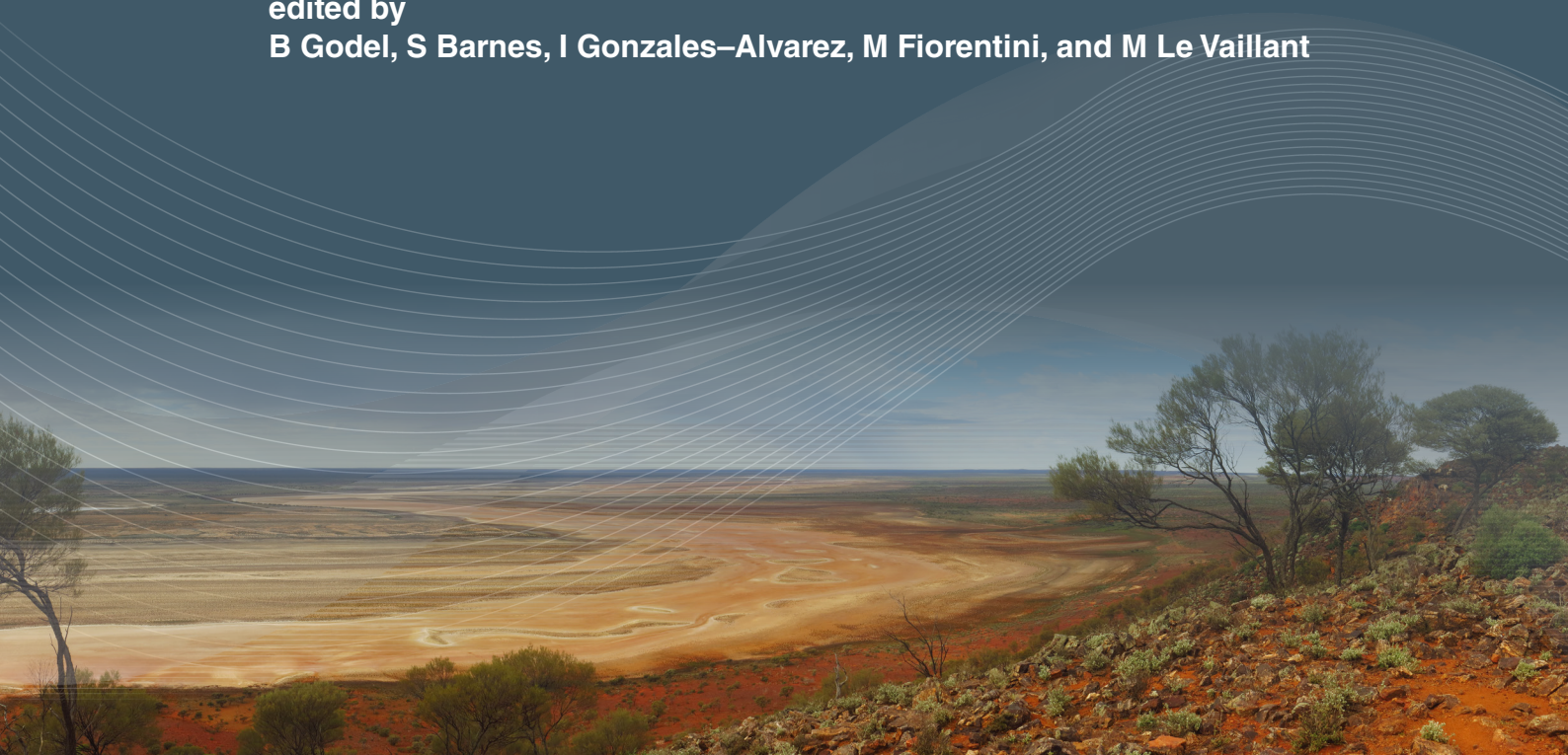
Government of **Western Australia**  
Department of **Mines and Petroleum**

RECORD 2016/13

# 13TH INTERNATIONAL NI-CU-PGE SYMPOSIUM, FREMANTLE, AUSTRALIA: ABSTRACTS

edited by

B Godel, S Barnes, I Gonzales–Alvarez, M Fiorentini, and M Le Vaillant



Geological Survey of  
Western Australia





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**Perth 2016**



**Geological Survey of  
Western Australia**

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**Cover image:** Elongate salt lake on the Yilgarn Craton — part of the Moore–Monger paleovalley — here viewed from the top of Wownaminnya Hill, 20 km southeast of Yalgoo, Murchison Goldfields. Photograph taken by I Zibra for the Geological Survey of Western Australia

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**PROGRAM - 13<sup>th</sup> International Nickel-Copper-PGE Symposium, Fremantle, Western Australia**  
**Wednesday 7<sup>th</sup> September 2016**

<b>Time From</b>	<b>Time To</b>	<b>Session</b>	<b>Chair</b>	<b>Speaker</b>	<b>Title</b>
8:00	8:15	<b>Registration and Conference Opening</b>			
8:15	8:30				
8:30	8:45	Albany-Fraser	TBC	<b>Catherine Spaggiari</b>	Tectonic setting of Ni-Cu mineralization in the Fraser Zone, Albany-Fraser Orogen, Western Australia
8:45	9:00				
9:00	9:15	Albany-Fraser	TBC	Wolfgang Maier	Petrogenesis and Ni-Cu sulphide potential of mafic-ultramafic rocks in the Fraser Zone within the Albany-Fraser Orogen, Western Australia
9:15	9:30	Albany-Fraser	TBC	Sebastian Staude	First underground geological observations at the Nova-Bollinger Ni-Cu-Co-sulphide deposit, Fraser Range, Western Australia
9:30	9:45	Exploration	TBC	<b>Mark Bennett</b>	Nova – found hidden in plain sight
9:45	10:00				
10:00	10:15	Exploration	TBC	John Simmons	PGE-(Ni-Cu) mineralisation at Dablo, Burkina Faso
10:15	10:30	<b>COFFEE / TEA BREAK</b>			
10:30	10:45				
10:45	11:00	Exploration	TBC	Nigel Cantwell	The role of geophysics in the Challa intrusive Ni-Cu-Co sulphide discovery at the Windimurra Layered Igneous Complex, Western Australia
11:00	11:15	Exploration	TBC	Fiona Best	Interpretive mapping using geophysical and soil geochemical data to maximise confidence in exploration targeting: An example from the previously unexplored Dido Ni-Cu-PGE prospect, Georgetown Region, northern Queensland
11:15	11:30	Exploration	TBC	Lynda Burnett	Nickel Copper Sulphide mineralisation at Akelikongo, North Uganda; discovery and geological setting.
11:30	11:45	Exploration	TBC	Chusi Li	Diverse geodynamic settings for major magmatic sulfide deposits in China: with exploration implications
11:45	12:00	Exploration	TBC	Karol Czarnota	Continental-scale mapping of Ni-Cu-PGE mineral system potential of Australia
12:00	12:15	<b>LUNCH</b>			
...	...				
13:15	13:30				

**PROGRAM - 13<sup>th</sup> International Nickel-Copper-PGE Symposium, Fremantle, Western Australia**  
**Wednesday 7<sup>th</sup> September 2016**

<b>Time From</b>	<b>Time To</b>	<b>Session</b>	<b>Chair</b>	<b>Speaker</b>	<b>Title</b>
13:30	13:45	Musgraves	TBC	<b>Zoran Seat</b>	The Nebo-Babel Ni-Cu-PGE and Succoth Cu sulphide deposits, West Musgrave, Western Australia
13:45	14:00				
14:00	14:15	Musgraves	TBC	Paul Polito	Ni-Cu-PGE and Fe-sulphide mineralisation in the West Musgrave region of Western Australia; learnings from a five year exploration program
14:15	14:30	Musgraves	TBC	Bartosz Karykowski	Geochemical characteristics of Cu-Ni-PGE mineralisation at the Manchego Prospect, Musgrave Province, Western Australia: Implications for exploration
14:30	14:45	<b>COFFEE / TEA BREAK</b>			
14:45	15:00	Hydrothermal / Lateritic	TBC	<b>Reid Keys</b>	The Avebury Nickel deposit, Tasmania, Australia: Key features of a significant hydrothermal nickel sulphide deposit
15:00	15:15				
15:15	15:30	Hydrothermal / Lateritic	TBC	Erick Ramanaidou	Lateritic Nickel Deposits
15:30	15:45				
15:45	16:00	Hydrothermal / Lateritic	TBC	Martin Wells	Hyperspectral imaging of Ni grade variability in the Goro Nickel Deposit (New Caledonia).
16:00	16:15	Hydrothermal / Lateritic	TBC	Anais Pages	Phosphorite and metal associations in the Cambrian metalliferous black shales of the Niutitang Formation
<b>Conference dinner</b>					

**Keynote**

**PROGRAM - 13<sup>th</sup> International Nickel-Copper-PGE Symposium, Fremantle, Western Australia**  
**Thursday 8<sup>th</sup> September 2016**

Time From	Time To	Session	Chair	Speaker	Title
9:00 9:15	9:15 9:30	Komatiite	TBC	Caroline Perring	New insights into the geodynamic setting of komatiite-hosted Ni-sulfide deposits in the Agnew-Wiluna Belt of Western Australia
9:30 9:45	9:45 10:00	Komatiite	TBC	David Mole	A new komatiite-hosted Ni-Cu-PGE event in the Eastern Goldfields Superterrane
9:45 10:00	10:00 10:15	Komatiite	TBC	Lauren Burley	The Fisher East nickel sulphide prospects
10:00 10:15	10:15 10:30	Komatiite	TBC	Stefano Caruso	Magmatic degassing of sulfide melt in komatiite: stratigraphy-controlled mineral assemblages, mineral chemistry and isotopic signatures in the Ni-PGE ores at Wannaway deposit, Eastern Goldfields, Western Australia
10:15 10:30	10:30 10:45	COFFEE / TEA BREAK			
10:45 11:00	11:00 11:15	Komatiite	TBC	Michel Houlé	Diversity of Ni-Cu-PGE mineralization and emplacement of the Black Thor-Double Eagle intrusive complexes of the Ring of Fire intrusive suite in the McFaulds lake greenstone belt, Oxford-Stull domain, Superior Province, northwestern Ontario, Canada
11:00 11:15	11:15 11:30	Komatiite	TBC	Heather Carson	Oxide chemostratigraphy of the Black Thor Chromitite Zone, Black Thor Intrusive Complex, McFaulds Lake, Canada
11:15 11:30	11:30 11:45	Komatiite	TBC	Charles Spath	Geology and genesis of Fe-Ni-Cu-(PGE) mineralization in the Black Label Hybrid Zone of the 2.7 Ga Black Thor Intrusive Complex, McFaulds Lake greenstone Belt, Ontario, Canada
11:30 11:45	11:45 12:00	Intrusion - PGE	TBC	James Austin	Exsolution, fractionation and magnetisation: Links between geophysical expression, architecture, cooling history and PGE prospectivity in the Giles Mafic-Ultramafic Intrusive Complex, Central Australia.
12:00 ...	12:15 ...	LUNCH			
13:15 13:30	13:30 13:45	Intrusion - PGE	TBC	Benjamin Wernette	Multiple S isotope studies of PGE enrichment in the J-M Reef, Stillwater Complex, Montana, USA
13:45 14:00	14:00 14:15	Intrusion - PGE	TBC	Tim Ivanic	The Windimurra Igneous Complex: an Archean Bushveld?

**PROGRAM - 13<sup>th</sup> International Nickel-Copper-PGE Symposium, Fremantle, Western Australia**  
**Thursday 8<sup>th</sup> September 2016**

<b>Time From</b>	<b>Time To</b>	<b>Session</b>	<b>Chair</b>	<b>Speaker</b>	<b>Title</b>
14:00	14:15	Intrusion - PGE	TBC	Lionnel Djon	High-PGE Low-Sulphur Stratiform Mineralization in the Layered Northern Ultramafic Centre of the Lac des Iles Complex, Ontario, Canada
14:15	14:30	Intrusion - PGE	TBC	Reiner Klemm	Platinum-group element concentrations in base-metal sulphides from the Platreef, Mogalakwena Mine, Bushveld Complex, South Africa
14:30	14:45	Intrusion - PGE	TBC	David Good	Evaluation of PGM as potential index mineral assemblages for high grade Cu-PGE deposits in the Coldwell Alkaline Complex, Canada
14:45	15:00	Intrusion - PGE	TBC	Raphael Baumgartner	The first in-situ minor and trace element analysis of sulphides in Martian magmatic rocks - unravelling the hosts of (highly) siderophile and chalcophile elements in some Shergottite meteorites
15:00	15:15	<b>COFFEE / TEA BREAK</b>			
15:15	15:30				
15:30	15:45	Characterization	TBC	<b>Ben Grguric</b>	Geometallurgy of low grade Ni sulphide deposits; challenges and success stories
15:45	16:00				
16:00	16:15	Characterization	TBC	Belinda Godel	Digital rocks: switching from 2D and 3D observation to 3D quantification.
16:15	16:30	Characterization	TBC	June Hill	Lumping geochemically-defined ore types in drill holes for simplified 3D modelling: an example from the Kevitsa Ni-Cu-PGE orebody, Finland
16:30	16:45	Characterization	TBC	Kono Lemke	Experimental and Theoretical Studies of Metal Speciation in Ore-Forming Vapors

**Keynote**

**PROGRAM - 13<sup>th</sup> International Nickel-Copper-PGE Symposium, Fremantle, Western Australia**  
**Friday 9<sup>th</sup> September 2016**

Time From	Time To	Session	Chair	Speaker	Title
8:00	8:15	Processes	TBC	C. Michael Lesher	The roles of xenoliths, xenocrysts, xenomelts, xenovolatiles, and skarns in the genesis of sulfide-rich magmatic Ni-Cu-(PGE) deposits and chromite-rich magmatic Cr deposits
8:15	8:30				
8:30	8:45	Processes	TBC	Anja Slim	Sulfide melt percolation and the origin of matrix ores: an analogue experimental study
8:45	9:00	Processes	TBC	Jesse Robertson	Particle clustering in eddies in chaotic laminar flows: a mechanism for accumulation of sulfide droplets from dynamic flows
9:00	9:15	Processes	TBC	Greg Dering	Dyke tips and melt pathways
9:15	9:30	Processes	TBC	Nicholas Arndt	Wet and moist komatiites – what is the source of the water?
9:30	9:45	Processes	TBC	Clément Ferraina	An experimental study of metal partitioning between sulphide liquid and mafic, ultramafic melts: the importance of oxygen fugacity
9:45	10:00	Processes	TBC	Alexander Cruden	Channelling magma flow in the crust to form magmatic ore deposits
10:00	10:15	Processes	TBC	Steve Barnes	Sulfide-matrix magmatic ore breccias: their origin at infiltration-melting fronts
10:15	10:30	COFFEE / TEA BREAK			
10:30	10:45				
10:45	11:00	Processes	TBC	Margaux Le Vaillant	Globular sulphide ores of the Noril'sk-Talnakh Ni-Cu-PGE deposits: insights into ore forming processes
11:00	11:15	Processes	TBC	Giada Iacono-Marziano	How to produce massive sulfide deposits by magma-sediment interactions: the Noril'sk-Talnakh case-study
11:15	11:30	Processes	TBC	Marco L. Fiorentini	Carbonatitic melt in deep seated mafic pipes physically entrains dense sulfide blebs during vertical magma flow
11:30	11:45	Intrusion - Ni	TBC	Edward M. Ripley	S, Os and Cu isotope variations between sheet- and conduit-style Ni-Cu-PGE mineralization in the Midcontinent Rift System, USA
11:45	12:00				
12:00	12:15	LUNCH			
...	...				
13:15	13:30				
13:30	13:45	Intrusion - Ni	TBC	Ya-Jing Mao	Genesis and exploration potential of the high Ni tenor magmatic sulfide deposits in the Eastern Tianshan, northwest China: constrains from PGE geochemistry and Os-S isotopes of the Huangshannan deposit

**PROGRAM - 13<sup>th</sup> International Nickel-Copper-PGE Symposium, Fremantle, Western Australia**  
**Friday 9<sup>th</sup> September 2016**

<b>Time From</b>	<b>Time To</b>	<b>Session</b>	<b>Chair</b>	<b>Speaker</b>	<b>Title</b>
13:45	14:00	Intrusion - Ni	TBC	Tom Járóka	Mafic dike-hosted Ni-Cu-Co (PGE) mineralization of the former mine Bergsegen, Sohland/Rožany, Germany/Czech Republic
14:00	14:15	Intrusion - Ni	TBC	Will Brownscombe	The geology and geochemistry of the Sakatti Cu-Ni-PGE deposit, N. Finland.
14:15	14:30	Intrusion - Ni	TBC	Ian Bliss	Ni-Cu-PGE prospectivity of the Labrador trough, Canada: Data from the Idefix and Huckleberry prospects of Northern Shield Resources
14:30	14:45	Intrusion - Ni	TBC	Joshua Smith	Sulfur isotope studies of Ni-Cu-PGE sulfide mineralization hosted in metasedimentary country rocks of the Midcontinent Rift System and the Stillwater Complex, USA
14:45	15:00	Intrusion - Ni	TBC	Bo Wei	Decoupling of the Re-Os and S isotopic systems in the PGE-depleted Ni-Cu sulfide deposits: insight for the role of crustal sulfur in sulfide saturation
15:00	15:15	<b>COFFEE / TEA BREAK</b>			
15:15	15:30				
15:30	15:45	Intrusion - Ni	TBC	Pedro Acosta-Góngora	Unravelling the genesis of Ni-Cu±PGE deposits in the south Rae craton, Canadian Shield: insights from the Thye Lake system
15:45	16:00	Intrusion - Ni	TBC	Hongjin Chen	Geochronological and Geochemical Constraints on Fe-Ni-Cu Sulfide Mineralization in the Xingdi-II Mafic-ultramafic Complex, Xinjiang, China
16:00	16:15	Intrusion - Ni	TBC	Rais Latypov	Melanocratic norite bodies of the Sudbury Igneous Complex, Canada: remnants of a tectonically-disrupted roof rock sequence?
16:15	16:30	Intrusion - Ni	TBC	Xie-Yan Song	The newly found giant Early Devonian Xiarihamu Ni-Co sulfide deposit in northern Tibet Plateau, China
16:30	16:45	Intrusion - Ni	TBC	Hannu Makkonen	Fennoscandian magmatic Ni-(Cu-PGE) deposits – composition of ore and parental magma through
<b>Closing of the conference</b>					

**Keynote**

PROGRAM - 13<sup>th</sup> International Nickel-Copper-PGE Symposium, Fremantle, Western Australia

## Poster display

Senior author	Poster Title
Evgeny Asafov	Parental melts of 3.3 Ga Barberton and 2.7 Ga Belingwe komatiites were significantly contaminated by seawater brines.
Eugen Ashu	Mineralogy and geochemistry of ultramafic rocks in Poli, Northern Cameroon.
Steve Barnes	Sword Blades and Hair Driers: Geometries and Emplacement Mechanisms of Ore-hosting Mafic-Ultramafic Intrusions.
Jarlen Beukes	Sulphide and PGE distribution in the 'Flatreef' at Turfspruit, Northern Limb of the Bushveld Complex, South Africa.
Maria Cherdantseva	PGE distribution in base metal sulfides from the Cu-Ni-PGE bearing Rudny intrusion, Tsagaan Shuvuut Ridge, North Western Mongolia.
Rosalind Crossley	PGE mobilisation in subduction zones and implications for ore deposit formation .
Maria Della Giustina	The Lago Grande Complex, Carajás Province, Brazil: insights into the remobilization of Pd-Pt through post-magmatic, low-temperature oxidizing fluids.
Belinda Godel	Mafic dykes and sills of the Capricorn Orogen (Western-Australia).
Nikola Groshev (presented by Bartosz Karykowski)	The Gabbro-10 massif with Fe oxide and PGE mineralization in the Monchegorsk layered complex (Russia): new data on whole-rock chemistry .
Florian Huthmann	News from the Bushveld: The world-class Waterberg PGE deposit, Limpopo Province, South Africa.
Tim Ivanic	Tracking down chromitite-hosted PGE behaviour and source(s) for the Windimurra Igneous Complex
Valery Kalugin	Platinum and Palladium Minerals in the Sulfide Globules from the Trill Offset Dike, Sudbury, Canada
Bartosz Karykowsky	Key characteristics of contact-style PGE-Cu-Ni mineralisation in the Early Proterozoic Monchegorsk Complex, Kola Peninsula, Russia
Yiguan Lu	Genesis of the Jinbaoshan PGE-(Cu)-(Ni) deposit, Western Yunnan, China: constraints from geochemistry of PGEs and mineralogy of base metal sulfides and PGMS
Aleskey Mekhonoshin (presented by )	Genesis of the Medek intrusion, Russia: evidence from fluid inclusions, mineralogy and geochemistry of platinum group elements
Anais Pages	Investigations of metal associations in the metalliferous black shales of South China and the Nick prospect by X-Ray fluorescence microscopy (XFM)
Henning Seibel	Mineralogical and petrographical characterization of Ni-Cu-(PGE)-enriched gabbroic dikes from the Hohwald (Lusatian Block, Bohemian Massif, Germany)
Sebastian Staude	Evidence of thermomechanical erosion of basalt by Fe-Ni-Cu sulfide melt at Kambalda.
Yao Zhuosen	Simulation for the partitioning behaviour of Ni in the partial melting of mantle under various tectonic settings



# Introduction to the 13th International Nickel-Copper-PGE Symposium

Esplanade Hotel, Fremantle, 7–9 September 2016

This Record contains the abstracts for the 13th International Nickel-Copper-PGE Symposium. Abstracts are arranged alphabetically by author and include both oral and poster presentations.

This meeting forms part of a long series of conferences on the topic of magmatic ore deposits of Ni, Cu and PGEs, held approximately biennially since 1978. The Ni-Cu-PGE meetings focus primarily on magmatic Ni-Cu dominated sulfide deposits. These alternate with the International Platinum Conferences which tend to focus on PGE-dominant ore deposits in layered intrusions as well as other PGE occurrences such as ophiolites, placer provinces and Alaskan complexes. The immediately preceding meetings to this one were the Ni-Cu-PGE meeting in Guiyang, China in 2012, and the 2014 International Platinum Conference in Ekaterinburg, Russia. The series will continue in 2018 with the 14th International Platinum Conference to be held in South Africa.

The Symposium is delighted to welcome our guest of honour, Dr Roy Woodall, legend of the Australian exploration scene from his ground-breaking days with Western Mining, and the major driving force behind the discovery and development of the Kambalda nickel field in the 1960s. This recognition comes appropriately in the 50th anniversary year of the discovery drill hole at Kambalda. Without the visionary work that led to that major discovery, none of us would be here, and Australia would be a poorer country.

The program presented here is designed to strike a balance between academic research developments and applications to the exploration and mining industry. It is arranged around a number of themes.

## Day 1

- The Albany-Fraser province and the Nova discovery. Keynote, **Catherine Spaggiari**, GSWA. The opening session of the meeting covers the most significant new Ni sulfide discovery in Australia in the last decade.
- Exploration case histories – keynote speaker **Mark Bennett**, S2 Resources, on the discovery of Nova connects the previous session with this one, covering discoveries and tectonic settings of deposits in Australia, Africa and China
- The Musgrave Province – new and known occurrences in a frontier exploration province in central Australia. Keynote **Zoran Seat** from Cassini Resources.
- Non-magmatic N deposits – laterites, sediment hosted and hydrothermal deposits. Keynote **Reid Keays**, Monash University.

## Day 2

- Komatiite-associated deposits, including the komatiite-associated oxide and sulfide deposits of the “Ring of Fire”, Ontario, Canada. Keynote Caroline Perring, BHP-Billiton.
- Intrusion associated PGE-rich magmatic sulfides, including the Platreef. Keynote **James Austin**, CSIRO.
- Characterisation of Ni-Cu-PGE sulfide ores - geometallurgy, orebody domaining and new experimental work. Keynote **Ben Grguric**, South Australian Museum.

## Day 3

- Physical processes in the formation of magmatic sulfide ores. Keynote: **Mike Leshner** (Laurentian Univ., Sudbury).
- Intrusion-hosted Ni-Cu-Fe sulfide deposits. Case studies of ore deposits and host rocks from around the world. Keynote **Edward Ripley**, Indiana Univ.

Selected papers arising from this meeting will be published in a special issue of Ore Geology Reviews, with Marco Fiorentini, Margaux Le Vaillant and David Mole as guest editors.

We are grateful to the sponsors of the Symposium (listed below). This sponsorship enabled us to offer travel subsidies to the international students attending the meeting.

The Symposium would not have been possible without the efforts of the organising committee.

Treasurer: Ignacio González-Álvarez (CSIRO)

Program: B  linda Godel (CSIRO)

Workshops: Margaux Le Vaillant (CSIRO)

Field trips: David Mole (CSIRO); Stephen Wyche (GSWA)

Publications: Marco Fiorentini (UWA – associate editor, special issue of OGR); Stephen Wyche (GSWA – abstract volume, field trip guidebooks)

Sponsorship: Steve Beresford (Centre for Exploration Targeting, UWA); Jon Hronsky (Western Mining Services)

GeoConferences representative: Ian Tyler (GSWA)

Website: Michael Vacher

Administrative and finance support: Cheryl Harris, Shannon Earnshaw, Tony Pinkpank (CSIRO)

We also thank organisers of previous conferences in the series, Mike Leshner, Sarah-Jane Barnes and Ed Ripley for helpful advice.

We hope you enjoy the meeting.

**Steve Barnes, CSIRO  
Chair**

August 2016

# Unravelling the genesis of Ni-Cu±PGE deposits in the south Rae craton, Canadian Shield: insights from the Thye Lake system

by

Pedro Acosta-Góngora<sup>1</sup>, Daniele Regis<sup>1</sup>, Sally Pehrsson<sup>1</sup>, Simon E. Jackson<sup>1</sup>, Edith Martel<sup>2</sup>

Important Ni-Cu-rich magmatic systems have long been recognized in the Churchill province of the Canadian Shield (e.g. Rankin Mine), but those of the lesser known southern Rae craton have previously been little studied. A number of metamorphosed norite-hosted Ni-Cu±PGE deposits (e.g., Thye Lake) and occurrences (e.g. Yotín Lakes) are found in the Rae craton of northern Saskatchewan and Northwest Territories. These metanorites are situated within and west of a major band of mylonites and tectonites termed the Snowbird Tectonic Zone (STZ) that forms the suture between the Rae and adjacent Hearne cratons. Until the current study, the only inferred constraints on the timing of mineralization came from the age of a paragneiss unit ~30 km away from the Thye Lake deposit that had a maximum depositional age of 2.02 Ga. Consequently, the metanorite intrusions were considered likely to have been emplaced post 2.02 Ga and prior to regional ca. 1.9 Ga tectonometamorphism. This time period broadly overlaps with formation of the Rae's Paleoproterozoic rift margins and the age of flood basalt magmatism in its marginal basins, plausibly emplacing Ni-Cu±PGE mineralization in a within-plate rift setting.

Recent U-Pb zircon geochronology results on samples from Currie, Yotín and Thye Lakes suggest that the intrusions are actually Archean (ca. 2.63 Ga) with a metamorphic episode recorded at ca. 1.9 Ga. The trace element geochemistry of the Thye Lake intrusions shows enrichment in large ion lithophile elements (LILE) and negative anomalies in Nb and Ti which are characteristic of arc-related intrusions. Also, evaluation of our data in tectonic setting discriminant diagrams further indicates a subduction environment, different from the more tholeiitic to alkaline 2.0 to 1.9 Ga Rae rift-magmatism. However, the S/Se values (1,300-16,600) of metanorite-associated ore suggest assimilation of crustal material, at least in terms of S. Similarly, an in-situ Cu isotopes study on chalcopyrite shows two distinct <sup>65</sup>δCu populations centred at ~ +0.3 and ~ -0.5‰ which can be interpreted as indicating magmatic and crustal sources, respectively. Alternatively, the lower <sup>65</sup>δCu population could record later metamorphic and/or hydrothermal events.

In summary, an Archean age and arc-like affinity for the south Rae Ni-Cu±PGE mineralization places it in a setting similar to that of Alaska-type deposits, and distinct from younger Paleoproterozoic systems. Moreover, crustal assimilation (S and Cu?) could have also played a significant role in the formation of these systems. In any case, the geochemical fingerprint of these intrusions could be used as a regional exploration tool in this largely underexplored terrane.

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# Wet and moist komatiites – what is the source of the water?

by

Nicholas Arndt<sup>1</sup>, Alexander Sobolev<sup>1</sup>, E. V. Asafov<sup>1</sup>

The original debate about the water contents of komatiites opposed two points of view: 1) almost all komatiites were essentially dry and formed in abnormally hot mantle plumes; 2) komatiites contained high water contents and formed in subduction settings. After years of discussion, opinion has tended to support the first hypothesis, mainly because accumulating of geological and geochemical data provided no convincing evidence of more than a fraction of a percent of water, nor of the characteristic trace-element signature of magmas from subduction zones.

Two recent studies have muddled the waters. The first focused on the Murphy Well flow in the eastern Yilgarn belt, Australia. The remarkable features of this flow – quench textures through the upper 20 m of the flow, near-uniform MgO contents through the whole flow (30-33%), and mismatches between measured and anticipated Fo contents of olivines – led Siegel et al. (2014) to conclude that the erupted lava contained up to 6% water. The second study focused on melt inclusions in olivines from the Alexo flow in the Abitibi belt of Canada. Using various geothermometers, Sobolev et al. (2016) showed that lava temperatures were about 50°C less than those of anhydrous liquidus. The presence of a small amount of water (about 0.6%) was confirmed by ion microprobe analyses.

In both cases a subduction origin was ruled out by trace element data which showed no sign of the subduction signature. For the Murphy Well flow, the water is thought to have been introduced via the assimilation of hydrated crustal rock such as serpentinite. For the Alexo flow, precise LAM-ICPMS trace-element measurements in melt inclusions demonstrated minor contamination of certain samples, but not those that crystallized the most magnesian olivine and contained the highest water contents. In this case, the water was introduced in the mantle transition zone, either via assimilation of a partial melt, or of water-bearing high-pressure phases like wadsleyite or ringwoodite.

## Reference

Siegel et al. (2014) *Contrib Mineral Petrol* 168:1084; Sobolev et al. (2016) *Nature* 531, 628–632.

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# Parental melts of 3.3 Ga Barberton and 2.7 Ga Belingwe komatiites were significantly contaminated by seawater brines

by

E. V. Asafov<sup>1</sup>, A.V. Sobolev<sup>1,2</sup>, A. A. Gurenko<sup>3</sup>, N.T. Arndt<sup>2</sup>, V.G. Batanova<sup>1,2</sup>, M.V. Portnyagin<sup>1,4</sup>,  
D. Garbe-Schönberg<sup>5</sup>, S.P. Krashennikov<sup>1</sup>, A.H. Wilson<sup>6</sup>, G.R. Byerly<sup>7</sup>

Komatiites are ultramafic rocks (MgO>18wt.%) that result from a high degree of mantle melting (commonly >30%) under extreme P-T conditions and hence represent its composition. A recent research of melt inclusions in highly magnesian olivines (Fo 92.4-Fo 94.2) in 2.7 Ga komatiites of the Abitibi Greenstone Belt, Canada (Sobolev et al., 2016) demonstrated an early contamination of melts by seawater inferred from high Cl concentrations. Yet the most magnesian olivines (Fo 94-94.5) hosted melt inclusions unaffected by the interaction with seawater that contained up to 0.8 wt.% H<sub>2</sub>O pointing towards the presence of a hydrous reservoir in the Neoarchean deep mantle.

Here we report new data on the water contents, other volatile elements, major and trace elements concentrations of melt inclusions in a range of olivines Fo 93-95.8 and, Fo 91-92.5 from the komatiites of the 3.3 Ga Weltevreden Formation, Barberton Greenstone Belt and 2.7 Ga Reliance Formation, Belingwe Greenstone Belt respectively.

Fresh olivine grains 0.2-0.5 mm across were heated for 5 minutes at 1400°C to 1500°C according to their composition in C-O-H atmosphere at the QFM buffer and rapidly quenched.

Weltevreden melt inclusions contain 0.2-0.8 wt.% H<sub>2</sub>O, 60 ppm to 0.22 wt.% Cl at MgO concentrations between 23-29.6 wt.% while Belingwe melts contain 0.23-0.52 wt.% H<sub>2</sub>O, 360 ppm to 0.14 wt.% Cl at 18.3-21.5 wt.% MgO. Weltevreden inclusions with high Cl contents (>0.1 wt.%) demonstrate positive correlation between chlorine and water contents pointing towards a possible seawater contamination whereas inclusions with lower Cl contents (0.03-0.1 wt.% of Cl) as well as all studied melt inclusions from Belingwe do not show such a correlation and thus may represent the source water. Still, Cl contents in most of the inclusions in both Belingwe and Weltevreden komatiites are much higher than expected for the mantle derived magmas and result from the seawater brine contamination. This interaction is indicated by the decrease in Na/Cl ratio in the melts tending towards the sea-water brines ratio.

The majority of melt inclusions hosted even in the most magnesium rich olivine was affected by the seawater brine contamination suggesting that this process started at an early stage of magma crystallization. Contaminated melts cannot be used for a robust reconstruction of the initial water contents. However, a small number of uncontaminated inclusions (<100 ppm Cl) that occur in the Weltevreden komatiites records the composition of primary melts and their mantle sources.

Recorded early contamination of komatitic melts compromises any attempts to reconstruct their primary H<sub>2</sub>O contents by studying products of their evolution.

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# Mineralogy and geochemistry of ultramafic rocks in Poli, Northern Cameroon

by

Ojong Eugen Lifanda Ashu<sup>1</sup>, Arnold Epanty<sup>1</sup>, Mboudou Germain Marie M.<sup>1</sup>, Tembi Atud<sup>1</sup>

The tectonic and magmatic evolution of Northern Cameroon is modelled by the development of an intracratonic basin which evolution is related to the major opening and the closure of the ocean along the West African craton. Three main successive tectonic events associated to collisional and post-collisional evolution were identified in the Cameroon domains including: crustal thickening; left lateral wrench movements; and right lateral wrench movements. The study site lies between latitude 8°24' – 8°32' N and longitude 13°12' – 13°28' E. The Poli series is one of the three groups that evolved during the Pan-African event. The Poli Group represents an early Neoproterozoic back-arc basin formed between 830 Ma and 665 Ma. The Poli basin may have been formed above a juvenile crust between two Paleoproterozoic domains, one inherited from the Congo craton (Adamaoua region) and the other somewhere in the north.

Field, petrographic and geochemical investigations of the rock samples revealed mafic – ultramafic rocks in the area. The rocks are generally black to dark grey color due to the presence of mafic minerals with medium to coarse grain sizes minerals due to slow cooling of the magma. Petrographically, the rocks samples contain: amphibole (euhedral to subhedral crystals), olivine (with many cracks of varying sizes), plagioclase (occurs as laths enclosing subhedral crystals of pyroxene), pyroxene (clinopyroxene) and hornblende (Pleochroic, from green to brown with phaneritic texture). Geochemically, the rock samples show very low SiO<sub>2</sub> (34.30 - 50.44 wt%), high MgO (0.19 - 20.10 wt%) and Fe<sub>2</sub>O<sub>3</sub> (8.93 - 38.62 wt%) but high concentration of Ni (6 – 448 ppm), Co (13 – 137 ppm), Cu (6 – 408 ppm), Cr (26 – 1910 ppm) and V (449 – 469 ppm) which are indicative of mafic - ultramafic rock. The concentration of Pt ranges between 5.5 and 19.0 ppb and the concentration of Pd between 6.9 and 24.9 ppb, indicative of potentials for PGE mineralization. Co Ni, Cu and Cr concentrations are above the detection limit while Au ranges between <1 – 4 ppb. V concentration is high in the weathered ultramafic rock.

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# **Exsolution, fractionation and magnetisation: Links between geophysical expression, architecture, cooling history and PGE prospectivity in the Giles Mafic-Ultramafic Intrusive Complex, Central Australia**

by

**James Austin<sup>1</sup>, Stephen Barnes<sup>2</sup> and Bélinda Godel<sup>2</sup>**

This study examines the relationships between platinum group element (PGE) prospectivity and magnetisation from a major mafic-ultramafic magmatic province, focussing on the processes that control the strength and stability of induced and remanent magnetism. Two geophysically distinct intrusions were sampled from the Giles Complex, and magnetic susceptibility, density and remanent magnetisation were measured. Results were interpreted in conjunction with a large geochemical database to identify the interrelationships between petrophysics and mineralisation.

The Mount Marcus intrusion causes a single sharp, high-amplitude negative magnetic anomaly corresponding with very strong, stable, relatively homogeneous remanence plunging moderately down toward the NW. The intrusion must have cooled relatively quickly in order to preserve its uniform mineralogy, and crystallised titanomagnetite at very high temperatures. However, the extreme magnetisation developed later, as the rock cooled through ~600°C and titanomagnetite was reduced to ilmenite with fine exsolution lamellae of magnetite. This intrusion represents a bladed dyke style target in which PGE prospectivity will be greatest at the base of the dyke.

By contrast, Mount Caroline is a much larger intrusion with distinct magnetic layering, characteristic of a layered intrusion. The alternating high and low magnetic anomalies correspond with two main phases. 1. Magnetite-rich anorthosite with predominantly induced magnetisation in multi-domain magnetite. 2. Gabbro and gabbro-norite which preserve stable remanence in single-domain magnetite, which is oriented moderately down toward the south. The lower horizons have a flat magnetic signature, corresponding with alternating layers of magnetite-poor pyroxenite and gabbro-norite. PGEs should sit in the lower cumulate phase of this intrusion. However, this is not necessarily true of other Giles intrusions, because the timing of sulfide saturation controls the localisation of sulfides. At Mount Caroline sulfide saturation is very early, which is why the upper magnetite-rich parts of the intrusion have no PGE potential. But, in other cases, the S-saturation event happens much later and can be correlated with the precipitation of magnetite, e.g., the Jameson Range, in the western Musgraves.

This study illustrates that the conditions required to create strong, stable, homogeneous remanence in a mafic intrusion are very different to those required to facilitate large-scale fractional crystallisation. Furthermore, the mechanisms by which magnetisation is acquired are intrinsically linked to both the intrusion architecture and cooling history. Therefore, insights into the magnetic properties and geophysical expression of mafic to ultramafic intrusions, coupled with knowledge of sulfide saturation, can be used to identify more prospective zones within target intrusions.

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# Sulfide-matrix magmatic ore breccias: their origin at infiltration-melting fronts

by

Steve Barnes<sup>1</sup>, Margaux Le Vaillant<sup>1</sup>, Peter Lightfoot<sup>2</sup>, Sebastian Staude<sup>3</sup>, Rubén Piña<sup>4</sup>

Breccia-textured ores, where magmatic sulfides form a matrix to rock fragments, are a widespread but generally understudied feature of many magmatic Ni-Cu-PGE sulfide deposits. They can be found in most deposit settings including komatiites, mafic-ultramafic chonoliths (Noril'sk, Nebo-Babel), sill-dike conduit systems (e.g. Voisey's Bay) and at Sudbury. In this study we investigated ore breccias from a number of deposits including Moran (Kambalda), Voisey's Bay, Aguablanca and Savannah (formerly Sally Malay), using a combination of 3D medical CT imaging and 2D microbeam XRF mapping. Magmatic breccias can be distinguished from tectonic breccias by a lack of penetrative shear fabrics, absence of pressure shadows and other strain features, and presence of delicate disaggregation textures resulting from partial or complete melting of enclosed silicate rock fragments. There is a complete spectrum from emulsion textures, consisting of intermixed silicate and sulfide liquids, to polymict sulfide-matrix breccias where clasts consist of a mixture of country rocks and host intrusion fragments, to infiltration zones where anastomosing sulfide-filled veins are injected into wall rocks. We consider that this spectrum also forms a continuum with net-textured ores and interspinifex ores, the unifying factor being that they are driven by gravitational percolation of dense, hot, low viscosity sulfide melt through the intercrystalline pore space of partially molten silicate rock. The complex polymict, vari-textured ore breccias at Voisey's Bay are generated when sulfide melt percolates through semi-consolidated silicate intrusion breccias, interacting with hydrous residual silicate melt that had partially crystallised to form a 3-dimensional plagioclase-olivine framework between refractory rock fragments. Heat from the sulfide melts the hydrous silicate component, leaving behind only the crystal framework and the partially disaggregated clasts, and displacing the silicate melt upward. The process, analogous to that observed on a smaller scale in interspinifex ores in komatiite settings, is self-reinforcing. As the column of interconnected sulfide liquid extends over a greater vertical distance, the hydrostatic head driving the downward percolation increases. At intrusion contacts, this forces sulfide liquid into fine fractures in underlying country rocks, causing country rock fragments to detach and become incorporated into the sulfide pool, where they can rapidly melt. Through this mechanism of downward stoping the sulfide pool can generate its own downward- or outward-propagating melting-infiltration front and enhance the propagation of the host intrusion itself. Rather than being passive traps, sulfide-filled embayments may be a consequence of this stoping process. We demonstrate case studies of these processes caught in the act.

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# Sword Blades and Hair Driers: Geometries and Emplacement Mechanisms of Ore-hosting Mafic-Ultramafic Intrusions

by

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Ore-hosting mafic-ultramafic intrusions come in a spectrum of shapes and sizes: channelised ribbon-shaped sills such as Noril'sk and Nkomati/Uitkomst; tube-like conduits such as Nebo-Babel and Limoiera; dyke-sill transitions such as Eagle, Huangshandong and Kalatongke with morphologies resembling hair-driers; and sword-blade shaped dykes with ultramafic cumulates at the bottom edge, exemplified by the intrusions of the Expo-Ungava South Raglan trend in the Cape Smith Belt, northern Quebec. Sulfide mineralisation in the latter two types commonly takes the form of cross-cutting, often breccia-textured bodies within the basal "keels". Of these types, the least widely recognised as potential hosts to mineralisation are the blade-shaped dykes. These are well known in shallow volcanic environments, often associated with extension, e.g. in Iceland and Hawaii. They are thought to form when a vertically propagating dyke starts to propagate laterally at a level of neutral buoyancy. Once the lateral extent exceeds the dyke height, magma flow is dominantly horizontal. In the case of the Expo-Ungava deposits, mineralisation is found at the bottom terminations of blade shaped dykes; the Savannah deposit (probably) and the Eagle's Nest deposit in the Ontario Ring of Fire have very similar geometries. This geometry may be more widespread than has previously been identified. The relatively common Eagle-Kalatongke type "hair-drier" intrusion morphology may form when magma flowing through an established blade-shaped dyke intersects more easily erodible country rocks, causing the dyke to widen into a tube. If so, the mineralization in the keels of such intrusions may be filling the basal termination of laterally propagating blades, rather than occupying the trace of upward injection of magma from a feeder dyke into a funnel, as in the conventional interpretations. The lenticular plan geometry of such deposits, Huangshandong being a prime example, may be due to the intersection of the erosion surface with the lower portion of a horizontally disposed lenticular blade, as in the Tootoo and Mequillon deposits of the South Raglan trend. Wide blade-shaped dykes and chonoliths may form a continuum. Emplacement and widening of initially blade-shaped intrusions would be accompanied by collapse of transient chilled margins and country rock xenoliths into the basal edge of the propagating dyke, and filling of this basal edge with crystals and sulfide liquid droplets. Subsequent downward percolation of coalesced sulfide liquid into the resulting partially consolidated pile of crystals and rock fragments could give rise to the distinctive sulfide ore breccias observed in many deposits including Aguablanca.

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# The first in-situ minor and trace element analysis of sulfides in Martian magmatic rocks — unravelling the hosts of (highly) siderophile and chalcophile elements in some Shergottite meteorites

by

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The Shergottites are igneous rocks that derived from potentially common mantle plume-related magma types on Mars. They share distinct chemical and mineralogical similarities with Archean and Proterozoic komatiites and ferropicrites, which are the hosts to economically important Ni-Cu-PGE sulfide deposits on Earth. Variable proportions (up to 1 vol.%) of dispersed (typically <50 microns) Fe-Ni-(Cu) sulfide assemblages are common constituents in the Shergottites. They presumably crystallized from discrete sulfide droplets that progressively segregated from the precursor melts. The latest technological advances in the in-situ LA-ICP-MS technique allowed us to analyze for the first time the micron-scale sulfide grains in some selected Shergottite meteorites (i.e., the olivine-phyric Shergottites Y-980459, DAG 476 and Dhofar 019, and the basaltic Shergottite Zagami) for relevant (highly) siderophile and chalcophile minor and trace elements (Ni, Co, Cu, PGE, Au, As, Se, Ag, Te, Pb, Bi).

In LA-ICP-MS analysis, the sulfides from Y-980459 are rarely the host to micron-scale Pt-rich nuggets. Despite these rare inclusions, most trace elements are contained in the sulfide species (pyrrhotite  $\pm$  pentlandite and Cu-sulfides). Overall, the sulfide assemblages from the olivine-phyric Shergottites show positive correlations between most minor and trace element contents, and the indexes of primitiveness of the host rocks (MgO content of olivine: Y-980459 > DAG 476 > Dhofar 019). Notable differences are the depletion of Rh and IPGE in sulfides from Y-980459 relative to DAG 476. The sulfides from the low-MgO Shergottite Zagami follow the general trend of decreasing siderophile-chalcophile element contents.

A major outcome of this study is the observation that the variation of siderophile-chalcophile elements in sulfides follows the trend of PGE whole-rock concentrations determined in previous studies, which suggests that sulfides are the main residence of PGE. However, the relatively low IPGE contents in sulfides from Y-980459 could also imply a separate host, such as IPGM away from sulfides. The PGE contents in sulfides from Zagami show good agreement with whole-rock analysis. However, the absence of detectable Pt contents contrasts with the bulk concentrations and the ratios between the PGE species in whole-rock analysis, and could suggest a separate host for Pt (e.g., Pt-rich PGM). Our data form a basis for the better understanding of the behaviour and mineralogical control of the (highly) siderophile-chalcophile elements in Martian igneous systems, and thus can aid to future studies dedicated to decipher how the planet evolved and whether (and where) precious metal-rich sulfide mineralization may have formed on Mars.

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## **Nova – Found hidden in plain sight**

by

**Mark Bennett<sup>1,2</sup>**

Well known examples of intrusive magmatic nickel-copper-cobalt-PGE sulfide deposits include Voisey's Bay in Canada, Kabanga in Tanzania, and Noril'sk in Russia. They are very rare and often very large, and new discoveries are very infrequent. The discovery of the Nova-Bollinger nickel-copper deposit in Western Australia in 2012 was therefore a significant event for the Australian exploration sector and the Australian nickel industry for a number of reasons.

It highlighted the fertility of an entirely new province, it sparked a modern day pegging rush, it reignited investor and market interest in exploration, it showed that Australia is not necessarily the mature exploration terrain that many think it is, and it proved that the Voisey's Bay deposit was not a one off.

It was also a classic rags to riches fairy-tale involving a small exploration company (Sirius Resources) being able to achieve what many larger companies had failed to do – to find a rare example of a large intrusive magmatic sulfide deposit. But what enabled Sirius to do this?

The story of the discovery process is in many ways a textbook example of simple but effective systematic exploration.

In hindsight, the signs were there at every stage of the process – ranging from its location in a Proterozoic mobile belt (the Albany-Fraser belt) bounding the edge of an Archaean shield (the Yilgarn craton) at a mega-scale, to the definition of strong surface geochemical and electromagnetic geophysical anomalies at a prospect scale, to the recognition of the presence of blebs of magmatic sulfides in reverse circulation drill cuttings at a micro-scale. But there were also many stages (and opportunities for error) between selecting a favourable tectonic terrain and securing title to it, and many more between this and identifying and selecting a specific prospect to test.

Additionally, there were also many false leads and instances of misinformation that could have derailed the process of testing the prospect through to the final discovery drill hole. These included a complete absence of PGE anomalism in initial surface geochemical sampling and subsequent reconnaissance drilling (with PGE's normally being a key indicator of magmatically derived nickel and copper enrichment), an association of nickel and copper enrichment with manganese in weathered rock (normally a key indicator of purely lateritic weathering processes rather than magmatically sourced sulfides), an apparent absence of obvious suitable host rocks (mafic-ultramafic intrusive), and a complete lack of anomalism of any metals in reconnaissance drilling directly over the geophysical EM anomaly that would normally be considered to represent massive sulfides at depth.

This presentation describes the entire story of how Sirius identified the opportunity, secured it, identified the target, systematically explored it to the point of defining a discrete drill testable bullseye, and, at a point when it looked too good to be true, had the courage to bet the company on it. It also describes the moment of discovery and the events of the ensuing frantic months and attempts to analyse why others with greater expertise and means didn't do the obvious.

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# **Interpretive mapping using geophysical and soil geochemical data to maximise confidence in exploration targeting: An example from the previously unexplored Dido Ni-Cu-PGE prospect, Georgetown Region, northern Queensland**

by

**Fiona Best<sup>1</sup> and Paul Polito<sup>2</sup>**

When it comes to exploration there is often a large volume of geological, geophysical and geochemical information available for interrogation, although this data is not always fully utilised. However, considered compilation and investigation of this data can allow robust exploration targeting in an informed and accurate way. The case study presented here is a previously unexplored Ni-Cu-PGE prospect, proximal to the SE margin of the Georgetown Region.

The area was identified for potential Ni-Cu-PGE mineralisation due to the known presence of a small number of olivine-bearing intrusive bodies proximal to crustal scale structures (i.e., the Tasman Line). Prior to commencing surface exploration, high resolution radiometric and aeromagnetic data was used to produce a regolith map of the entire prospect. This process identified 14 predominantly unknown mafic-ultramafic intrusions based on their depleted K-U-Th and strong magnetic signatures. Further, mapped areas of thick or recently transported cover, represented by highly anomalous K-U-Th signatures, were identified and these areas were able to be avoided during soil sampling.

Soil sampling occurred over the two largest mapped mafic-ultramafic intrusions – Palmer North and Palmer South. Samples were analysed using aqua regia digest and 53 elements were reported. The soil sampling program highlighted that these two intrusive bodies are geochemically and compositionally different. Whereas the Palmer North intrusion is characterised by anomalous levels of Mg, Cr, Co, Ni and Cu relative to background, the Palmer South intrusion is characterised by anomalous Fe, V, Cu, Sc, Co and Pt relative to background. Both were regarded as being prospective for Ni-Cu-PGE sulphides but, due to their contrasting background Ni and Cu levels, the intrusions needed to be interrogated separately to identify drilling targets. Statistical assessment of data defined background levels and threshold limits for commodity elements and percentile maps and robust Tukey outliers then identified areas for drilling. Sub-economic sulphide mineralisation was intersected in both intrusions.

This case study demonstrates that, in combination with geophysical mapping tools, multi-element soil geochemistry can clearly and accurately map significant differences in covered geology. When interpreted correctly this has implications for setting baseline threshold limits for direct detection elements such as Cu, Ni, Co, Cr, Pt and Pd. In this example, it is likely that the Palmer South intrusion would not have been tested if the baseline thresholds had been statistically determined from the entire dataset.

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## **Sulfide and PGE distribution in the ‘Flatreef’ at Turfspruit, Northern Limb of the Bushveld Complex, South Africa**

by

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This study will investigate the ‘Flatreef’ orebody at the Turfspruit farm, which is in the Southern sector of the Northern Limb of the Bushveld Complex. The ‘Flatreef’ is the flat to gently dipping down-dip extension of the original Platreef discovery. The stratigraphy of the Northern Limb, in which the Platreef is found, is not consistent, and magmatic unconformities are inferred. This applies especially in the lower parts of the Platreef stratigraphy where the mineralisation is concentrated. Although numerous investigations have been done on the Platreef, the accepted genetic models still require refinement for laterally variable reef sections in specific places. Therefore, this initial study will be focusing on trace elemental and isotopic characteristics of mineral quantifying country rock contamination of the magma at Turfspruit. The investigation aims at understanding the role of crustal contamination in the mineralization process and the identification of magma replenishment in the Flatreef.

The main objectives of this study are: a) to establish the effect of country rock contamination and assimilation on sulfide immiscibility and PGE scavenging as ore-forming processes on a microscale; as well as the characterisation of mineral textures, chemical zonation and isotopy using Tornado  $\mu$ -XRF, LA-ICP-MS, SIMS and FE EMPA; b) to validate models for sulfide formation by comparing S isotopes of disseminated sulfides with sulfide inclusions in chromite; and c) to visualise the behaviour of sulfide melt in the cumulus mush of the Flatreef in order to quantify the distribution of sulphides, and possible PGMs in 3D by the use of High Resolution X Ray Computed Tomography.

Two drill holes intersecting the Critical Zone of the Flatreef were sampled at approximately 3 meter intervals. Preliminary microscopy shows that silicates, such as olivine, have undergone serpentinisation and that interstitial plagioclase is mainly altered to sericite in altered samples. Late stage alteration is prominent along microstructures, producing secondary silicates such as tremolite and actinolite, which replace primary sulfides and remobilise sulfides along veins in the T1 feldspathic pyroxenite. A mixed of magmatic-sedimentary-meteoric fluid source is assumed. However, this needs to be confirmed by O isotopes.

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# Ni-Cu-PGE prospectivity of the Labrador trough, Canada: Data from the Idefix and Huckleberry prospects of Northern Shield Resources

by

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The Labrador trough is an early Proterozoic (2.17-1.87 Ga) volcanosedimentary belt with a complex geological history. Most of the rocks formed in a continental rift setting during break-up of the Kenorland supercontinent, from ~ 2.2 Ga to ~ 1.87Ga. Three cycles of sedimentation and volcanism occur (Clark and Wares, 2005). In the first cycle (2.17-2.14 Ga) a rift sequence was deposited at the NE margin of the Superior craton (conglomerates, alkaline volcanics), overlain by passive margin sediments, and then (during renewed rifting) MORB-type basalts, dolomites, and sediments. After a 200 Ma period of magmatic quiescence, a second cycle (1.88-1.87Ga) formed more sediments, BIF, alkaline magmas (carbonatites, meimechites), MORB-type basalts, and pyroclastics. Both cycles contain abundant mafic-ultramafic sills (named “Montagnais sills”, exposed over an area of 500 x 50 km) that are coeval with the basalts. The third cycle consists of synorogenic molasses. On a regional scale, the Labrador trough forms part of the circum-Ungava geosyncline and the Trans Hudson orogeny that also hosts the Thompson and Raglan Ni belts. It has been suggested that these deposits are related to a global mantle overturn event resulting in slab avalanches and several large plumes that ultimately led to the amalgamation of the Columbia (Nuna) supercontinent. The second cycle could represent transpressional reactivation of the suture zone along which the Kenorland supercontinent rifted.

The large amount of mafic-ultramafic intrusions and basaltic lavas in the Labrador trough suggests enhanced magmatic sulfide potential. Only relatively small Ni-Cu-PGE deposits have been found so far, possibly implying that larger deposits remain undiscovered. Here we report on recent discoveries of Ni-Cu-PGE sulfides at Northern Shield’s Idefix and Huckleberry prospects. Idefix is located 90 km NW of Kuujuaq. It is interpreted to represent a thick mafic-ultramafic sill formed mostly from relatively differentiated magma (5-6% MgO) that initially formed through large degree melting of the mantle. Drilling and surface sampling proved the existence of reef type mineralization averaging 0.2-0.4 g/t PGE over 16-34 meters that can be traced for 7 km. Peak grades reach 16 g/t Pt+Pd (Pt/Pd 1:3). The presence of large (up to 3cm) Ni-Cu-PGE bearing sulfide globules observed in every drill hole points to the possible existence of nearby massive magmatic sulfides. Preliminary analysis of these globules show grades on the order of 2% Ni, 4% Cu and 20 g/t PGE. Sulfide melt segregation could have been triggered by addition of external S from adjacent S bearing host rocks.

Huckleberry is located 350 km SE of Idefix, and 100 km N of Schefferville, Quebec. Mineralisation has so far been traced along a strike length of 3 kilometers, with 70 samples yielding an average of 1.10 % Cu, 0.21 % Ni and 0.87 g/t PGE+Au. However, relatively Ni rich samples have also been found, eg with 1.17 % Ni, 0.83 % Cu & 1.08 g/t PGE+Au. The richest sample contains 10.6 wt% Cu and 16.9 ppm PGE+Au. The host rocks are gabbros with Mg# similar to Idefix, suggesting a broadly similar magmatic lineage. The relatively high Cu/Ni ratios in most samples are interpreted as a result of mss fractionation.

## Reference

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## The geology and geochemistry of the Sakatti Cu-Ni-PGE deposit, N. Finland

by

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The Sakatti Cu-Ni-PGE (platinum group elements) deposit is a newly discovered mineral deposit in northern Finland. The deposit is a magmatic sulphide hosted in a tubular ultramafic intrusion in the Central Lapland Greenstone Belt. The major lithologies and styles of mineralisation of the deposit have been characterised.

The host rock is composed primarily of olivine with forsterite content between 0.85 and 0.91 and a Ni content between 3000-3700 ppm. The intrusion sits within a plagioclase-picrite footwall and hanging wall, and the locus of the deposit occurs at a change in gradient where the intrusion transgresses to a higher lithology. Sulphide has collected at this deflection of the conduit body and also intruded into the footwall unit as massive sulphide dykes.

Sulfur isotope analysis shows that the Sakatti deposit has consistent  $\delta^{34}\text{S}$  values between 0 ‰ and 4.5 ‰. This is not consistent with the regional Matarakoski schists contributing S to the deposit. The deposit has unusually low Ni/Cu values, particularly the shallower portions. The Ni/Cu values vary spatially, from low (<0.1) in the shallow SE part of the deposit to high (~1-2) in the deeper NW end of the deposit. This is true of both disseminated and massive sulphide. Magnetite trace element analysis, PPGE/IPGE values and Ni isotope analysis presented may suggest that this is due to sulphide fractionation and loss of early fractionating Ni-rich sulphide cumulates.

The PGE mineralogy in the Sakatti deposit is exclusively PGE tellurides, derived from sulphide melt. The dominance of tellurides leads to a wide array of moncheite-merenskyite-melonite compositions that is not seen elsewhere.

A model is presented for the formation of the deposit where sulphide melt accumulates at an earlier stage in the conduit-like intrusion, Ni-rich sulphide cumulates are deposited and the residual sulphide is magmatically remobilised by later silicate melt that does not re-equilibrate with the sulphide melt.

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# The Fisher East nickel sulfide prospects

by

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Until recently, the Kurnalpi and Burtville Terranes have been considered by many to be poorly endowed in komatiite-hosted nickel sulfide deposits, particularly compared to the neighbouring Kalgoorlie Terrane, which is known for hosting world class examples. However, the presence of large mafic-ultramafic belts in these two terranes and recent discoveries of such deposits suggest these terranes could be equally prospective, but under-explored. Prospectivity of the Kurnalpi Terrane was tested by comparing lithogeochemical and mineralogical characteristics of nickel sulfide-mineralized komatiites at the newly discovered Fisher East prospects, with komatiites from the highly nickel endowed Kalgoorlie Terrane.

Fisher East komatiites are pervasively altered to talc-carbonate assemblages, with no preservation of primary textures. Despite this, upper A zones (probably originally spinifex textured) and lower B zones (olivine cumulates) can be distinguished based on secondary textures, hyperspectral data and geochemistry. B zones are commonly much thicker at Fisher East, and contain higher proportions of talc, MgO and Ni than A zones, which have higher proportions of chlorite, Al<sub>2</sub>O<sub>3</sub>, Zr and Ti. These characteristics, along with elevated Ni/Ti and Ni/Cr imply Fisher East komatiites were domains of higher magma flow, resulting in olivine cumulates, but not olivine adcumulates which are seen in the big deposits of the Kalgoorlie Terrane. Features of the Fisher East komatiites are consistent with eruption in a channelized sheet flow environment, similar to the type facies architecture envisaged at Kambalda.

Further geochemical analysis reveals Fisher East komatiites were sourced from shallow depths in the mantle as indicated by Al<sub>2</sub>O<sub>3</sub>/TiO<sub>2</sub> ratios, while elevated incompatible trace element ratios show high degrees of crustal contamination. Crustal contamination is also evident in drillcore, shown by 'rip-up' clasts of substrate material and sulfides invading the footwall. Both of these traits are common in mineralized komatiites in the Kalgoorlie Terrane. Komatiite-hosted nickel sulfide deposits in the Kalgoorlie Terrane are dominated by type 1 and 2 style mineralization, with Fisher East also showing type 1 characteristics.

Through studies at Fisher East, it has been found that the north-eastern Kurnalpi Terrane displays many important ingredients for hosting large nickel sulfide deposits: evidence for magma systems showing high flux, cumulate-textured komatiites and proof of crustal contamination. Further work, including the generation of new geochronological data, will be vital for interpreting the Kurnalpi-Burtville region and for assessing its potential for it to be a major nickel province in Western Australia.

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## Nickel Copper Sulfide mineralisation at Akelikongo, North Uganda; discovery and geological setting

by

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Systematic conventional mineral exploration has resulted in the discovery of a significant nickel copper sulfide mineral system in Northern Uganda. Open-hole drilling of a Ni-Cu-PGE soil anomaly on 17th June 2014 intersected an “unclassified mafic to ultramafic” lithology in LMR002 running >0.1% Cu and >0.4% Ni at the end of hole sample (35-38m), resulting in the discovery of Akelikongo and the Akelikongo Ultramafic Complex (AKUC).

The AKUC is one of a number of ultramafic intrusions situated in the neo-Proterozoic aged Karamoja Domain, which is dominated by paragneisses. The Karamoja domain is thrust from north east to the southwest over the Proterozoic to Archean Palabek Aswa and Congo Domains marking the northeastern margin of the Congo supercraton. The AKUC has been defined by drilling, geological logging, petrography and geochemical analysis as a high MgO (>25% MgO) magmatic host intrusion. The majority of this intrusion comprises an orthopyroxene-oikocrystic olivine cumulate with minor clinopyroxene. No significant serpentinisation of these ultramafic rocks has occurred.

A Footwall Mixing Zone is present on the margins of the AKUC, typically about 20m wide, with heterogeneous igneous compositions, ranging from pyroxenite, through gabbroic, to felsic and complex, variable textures that represents the crystallisation of a hybrid melt derived from the AKUC and footwall paragneiss. The upper contact of the AKUC has not been yet intersected. The AKUC is cross cut by several generations of late intrusions including granitic and felsic pegmatitic dykes.

Accumulations of matrix to massive Ni-sulfide are closely associated with paragneiss clasts and felsic xenomelt within the Footwall Mixing Zone; overlying this zone the olivine cumulates of the AKUC hosts disseminated nickel sulfides. This disseminated mineralisation grades up to 0.6% Ni and shows classic intercumulus magmatic textures. The magmatic sulfide mineralisation comprises pentlandite, chalcopyrite, pyrrhotite and minor pyrite and generally increases in abundance toward the footwall mixing zone with an average Ni tenor of 5.3 wt. %. Levels of platinum-group-elements in the Ni-sulfides are low where assayed, usually significantly less than 1ppm.

The AKUC is interpreted to be a plunging chonolith or conduit that has had a high magma flux which interacted with the country rock during emplacement to form a magma mixing zone where massive sulfide mineralisation has accumulated. The potential for extensive zones of massive sulfide at AKUC lies deeper, towards the inferred base of the conduit channel and along its down-plunge extent to the North West, particularly in any position where the base of the chonolith flattens.

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# **The role of geophysics in the Challa intrusive Ni-Cu-Co sulfide discovery at the Windimurra Layered Igneous Complex, Western Australia**

by

**Nigel Cantwell<sup>1</sup>, Jayson Meyers<sup>1</sup>, Nick Corlis<sup>2</sup>, Graeme McDonald<sup>3</sup>, John Brennan<sup>2</sup>**

The large Windimurra Layered Igneous Complex occurs in the Murchison-Youanmi terrane of the Archaean Yilgarn Craton in Western Australia. It is comprised of several coalescing mafic-ultramafic lopoliths surrounded by granite and gneiss, which were deformed by folding, shearing and faulting. Igneous layering and structures have been mapped in outcrop, drillholes and open cut mining, and are traced under regolith cover by airborne and ground magnetic survey data. The exposed mafic upper parts of the lopoliths have been successfully explored for reef style PGE mineralization and vanadium in magnetite gabbro, with vanadium having been mined along the Shepherd's Discordant Zone. The current level of erosion has exhumed only the upper mafic levels of the lopoliths, and little exploration has been focussed on targeting Ni-Cu sulfide bearing magma conduits or chonoliths, which are normally expected to occur deep below the lower ultramafic zones at the base of the complex, estimated to be as deep as 7 km below present land surface based on geological layering, modelling of gravity data, and deep seismic reflection profiling.

In late 2012, Flinders Mines Ltd held mineral rights over a majority of the complex when the Challa intrusive Ni-Cu-Co sulfide bodies were discovered. A review of historical geophysical data was completed by geophysical consultants Resource Potentials, which involved re-processing and analysis of open-file 400m line-spaced REPTM helicopter electromagnetic (HEM) data, and grid merge and processing of various airborne magnetic datasets with different survey line spacing and resolution. Two subtle and discrete late time HEM anomalies stood out in the HEM data as having potential to represent bedrock conductors alongside of the Shepherd's Discordant Zone in the southeast portion of the ultramafic complex (targets CG002 and CG039). These HEM anomalies had the appearance of false anomalies caused by superparamagnetic (SPM) effects formed over a magnetite ridge, but they also coincided with Ni and Cu soil geochemical anomalies and discrete ground and airborne magnetic anomalies. Therefore they were followed up with moving loop ground electromagnetic (MLEM) surveys that confirmed the source of both HEM anomalies to be caused by discrete bedrock conductors and not SPM effects. The MLEM data provided much greater confidence and locations to drill test the conductors. Flinders Mines drill tested the two MLEM anomalies, and all 7 RC drillholes intersected semi-massive to massive Ni-Cu-Co bearing sulfide mineralization hosted in a steeply dipping, zoned pyroxenite surrounded by layered gabbroic country rocks. Downhole electromagnetic (DHEM) surveying also helped to identify the geometry of the conductive ore bodies forming multiple thin zones extending away from the drillholes. Mineralization is thought to be part of a late intrusive event that formed along the western side of the Shepherd's Discordant Zone as small magma conduits intruded through the higher level, vanadiferous magnetite gabbro portion of the complex.

The two main HEM anomalies were also detected in the data acquired with a VTEM survey, which show discrete circular magnetic anomalies associated with the Ni-Cu-Co sulfide discoveries that were not obvious in broader 400m line-spaced open-file magnetic data. Although the drilled intersections at Challa targets CG002 and CG039 may be uneconomic at this stage, the VTEM survey has identified a number of additional late time EM anomalies in the area that remain prospective exploration targets for Ni-Cu sulfide mineralization.

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## Oxide chemostratigraphy of the Black Thor Chromitite Zone, Black Thor Intrusive Complex, McFaulds Lake, Canada

by

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The ca. 2.7 Ga Black Thor Intrusive Complex (BTIC) is a ~10 km long x 2 km thick x 1 km wide (open at depth) ultramafic-mafic conduit system in the McFaulds Lake greenstone belt, northern Ontario. It hosts the Black Thor (BTCZ) and Black Label Chromitite Zones that contain up to 100 m and 30 m, respectively, of chromitite with grades up to 50 wt% Cr<sub>2</sub>O<sub>3</sub>, averaging 31 wt% Cr<sub>2</sub>O<sub>3</sub>. There is much debate on the mechanisms for the formation of these type of deposits, particularly how to produce such great thicknesses of chromite in relatively small intrusions from a magma that contains only ~3000 ppm Cr. The amount of chromite is too great to have crystallized due to contamination, oxidation, or any of the many other models that have been proposed for much thinner chromitite accumulations, and there is no evidence in the silicate mineralogy to support a model involving mixing of a more evolved with a more primitive magma to crystallize so much chromite.

An alternative mechanism, currently under investigation, involves partial assimilation of oxide-silicate facies iron formation (OXIF) and/or gabbroic rocks during magma ascent/emplacement. Wholesale assimilation of OXIF is not a viable mechanism for generating chromite, as the presence of olivine-chromite in  $\geq$  cotectic proportions throughout the intrusion indicates that the parental magma was saturated in chromite. However, assimilation of the silicate component would explain the Opx-rich nature of the intrusion, and disaggregation, transport, and upgrading of residual magnetite to chromite via interaction with the Cr-rich parental magma would explain the large amount of chromite. Magnetite-rich xenoliths containing reverse-zoned chromite identified along the basal contact of the BTIC and in the adjacent Eagle Two Ni-Cu-(PGE) prospect may represent material that was not disaggregated and only partially upgraded.

The chemistry of chromite in a drill core that intersect a 68m-thick section through a structurally and magmatically undisturbed portion of the BTCZ has been analysed by EPMA WD-XRES. Chromite cores display only small variations in Cr-Ti-V-Mg with only minor exchange of Mg and Cr. Mg# (Mg/(Mg+Fe)) and Cr# (Cr/(Cr+Al)) of chromite-rich lithologies, that are least affected by serpentine alteration, typically range 28 - 50 and 68 - 72 respectively. The variation in Mg# is directly related to the abundance of olivine, and appears to be an effect of re-equilibration with trapped liquid, whereas the variation in Cr# appears to be a result of changes in magma composition and/or the silicate-oxide ratios (R factor).

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# Magmatic degassing of sulfide melt in komatiite: stratigraphy-controlled mineral assemblages, mineral chemistry and isotopic signatures in the Ni-PGE ores at Wannaway deposit, Eastern Goldfields, Western Australia

by

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Boswell Wing<sup>4</sup>, and Laure Martin<sup>2</sup>

We have studied an 18 m-long UWA-04-02 drillcore that intersected the entire thickness of the Wannaway Ni-PGE ore deposit on the Widgiemooltha Dome. In spite of regional deformation and metamorphism, this portion of Archean greenstone still preserves part of its original textures and assemblages from both the footwall sulfidic metasediments and the magmatic orebody, where basal massive sulfides grade upward to net-textured and disseminated into the komatiite host. Systematic mineralogical and chemical variations of sulfides, spinels and silicates down the hole reflect variations of ore forming conditions. The ore assemblage consists of Fe sulfide and pentlandite, with minor sphalerite and chalcopyrite, spinels (chromite, Ti-magnetite), alabandite (MnS), accessory PGE-rich sulfarsenides and tellurides and rare molybdenite. Monoclinic and high-S hexagonal pyrrhotite and unaltered, disseminated Zn-Mn-rich chromite characterize the basal massive facies, whereas the matrix ore facies is marked by magnetite and sphalerite in a S-depleted and reduced assemblage, now represented by troilite exsolving low-S hexagonal pyrrhotite and alabandite. Spinel record progressive accumulation of oxygen exsolved from the sulfide melt: massive ore chromites gradually increase their ferric and V components upwards until the transition to matrix ore where magnetite dominates. Compositional modifications in FeS across the whole orebody and occurrence of alabandite testify progressive sulfur loss accompanied by establishment of low  $fO_2$  conditions over several meters up-sequence in the matrix ore facies. Fresh olivines intergrown with matrix ore facies sulfides show gradual decrease of Fe, Mn and Zn contents towards the barren hangingwall komatiite. Olivine-sulfide Fe-Ni partitioning confirms low  $fO_2$  conditions established across the matrix ore facies.

Mineralogical and chemical features could have derived from an original, complex pattern of devolatilization (sulfur and oxygen) from the sulfide melt. This hypothesis is further supported by the in-situ multiple sulfur isotope signatures of FeS-pentlandite pairs across the ore sequence. Constant  $\Delta^{33}\text{S}$ - $\delta^{34}\text{S}$  values among pairs outline the isotopic equilibrium of the sulfides and their high-temperature affinity. The uniform positive mass-independent ( $\Delta^{33}\text{S}$ ) signatures of the magmatic sulfides clearly reflect a sedimentary sulfur source similar to the footwall metasediments. Furthermore, the remarkable stratigraphically-controlled shift in  $\delta^{34}\text{S}$  from heavier to lighter values is evidence against influence of metamorphic processes that would otherwise homogenize the mass-dependent ( $\delta^{34}\text{S}$ ) signatures. On the other hand, this isotopic pattern copes with a process of magmatic degassing in a komatiite lava flows involving sulfur loss via emission of volatiles.  $\text{SO}_2/\text{H}_2\text{S}$  ratio would decrease concentration of heavy sulfur isotopes in the segregated sulfide liquid.

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# Geochronological and geochemical constraints on Fe-Ni-Cu sulfide mineralization in the Xingdi-II mafic-ultramafic complex, Xinjiang, China

by

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The Xingdi-II mafic-ultramafic complex is located in the northern margin of the Tarim Craton, Northern Xinjiang, NW China. This complex is mainly composed of gabbro, gabbro norite, olivine websterite and lherzolite. Sulfide mineralization is associated with the ultramafic rocks. Here we report zircon U-Pb ages, major mineral compositions, whole rock major and trace element concentrations, whole rock Sr-Nd isotopes, zircon Hf-O isotopes and S isotopes of sulfides. Zircon crystals from a large gabbroic sample from the center of the complex yield a U-Pb age of  $744 \pm 4$  Ma, about 16 Ma younger than the previously-reported zircon U-Pb age for the same type of rock that occurs in the southern part of the complex. The protracted nature of magma emplacement in the complex is consistent with arc basaltic magmatism instead of mantle plume activity thought previously. The mafic-ultramafic intrusive rocks all show light REE enrichments and pronounced negative Nb anomalies. Olivine crystals from the ultramafic rocks are all significantly depleted in Ca (<1000 ppm) but have contrasting Ni contents that cannot be explained by in situ fractional crystallization alone. The Xingdi-II mafic-ultramafic rocks are characterized by  $(^{87}\text{Sr}/^{86}\text{Sr})_i$  ratios from 0.7061 to 0.7086 and  $\epsilon_{\text{Nd}}(t)$  values from -9.2 to -5.1. The  $\epsilon_{\text{Hf}}(t)$  and  $\delta^{18}\text{O}$  values of zircon crystals from the mafic rocks range from -3 to -13 and from 7.1 to 9.2‰, respectively. The isotope data indicate that the parental magma was derived from an enriched source mantle and experienced significant contamination with old crustal materials, supporting the interpretation of a continental arc setting for this complex. The  $\delta^{34}\text{S}$  values of sulfides range from 2 to 4‰, slightly higher than typical mantle value ( $0 \pm 2\%$ ), indicating that the sulfide mineralization is related to addition of crustal S.

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# **PGE distribution in base metal sulfides from the Cu-Ni-PGE bearing Rudniy intrusion, Tsagaan Shuvuut Ridge, North Western Mongolia**

by

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The Devonian Rudniy intrusion (NW Mongolia) is one of numerous gabbroic intrusions surrounding the Tuva depression and considered part of a large igneous province. However, Rudniy is the only one known to contain magmatic sulfide Ni-Cu-PGE mineralisation (as disseminated sulfide blebs, ranging from 3 mm to 30 mm in size). The blebs are zoned and consist of pyrrhotite, pentlandite, chalcopyrite and cubanite. The intrusion is of interest because it is a small intrusive body that solidified quickly and the sulfide blebs are interpreted to keep a record of the geochemical behaviour of chalcophile elements from the crystallisation of a sulfide melt in a closed system. This is significant because the behaviour of chalcophile elements during the formation of large-scale Cu-Ni-PGE deposits is still controversial due, at least in part, to later alteration and hydrothermal processes that may have strongly affected the resulting distribution of elements. Detailed characterization of the sulfide blebs show that the base metal sulfides (BMS) contain platinum-group mineral as small nuggets and in dispersed form. Using LA-ICP-MS and ICP-MS analyses the concentrations of chalcophile and platinum group elements in the BMS were measured. Chondrite-normalized PGE and precious metal concentrations in 100% sulfides from Rudniy intrusion were plotted for three types of blebs sampled in outcrops (which differ in shape, size, enrichment in PGE, and abundance of precious metal nuggets). Comparison with published data compilations indicates that the sulfide blebs are consistent with the trend pertaining to flood basalt ores. All samples analysed have very similar patterns except for Os and Ag, which may indicate that these two elements are sensitive to fractionation processes. The distributions of PGE and precious metals in pentlandite seem to indicate that pentlandite is not exsolved directly from monosulfide or intermediate solid solution and instead formed due to the reaction between mss and residual Cu-rich sulfide melt. Furthermore, partition coefficients between mss and sulfide liquid were calculated for

PGE and precious metals. With the exception of Ag and Pd, the calculated partition coefficients (for Re, Ir, Ru, Pt, Au, Cd and Zn) are similar to those found in published experimental work and comparable with data from Noril'sk ores. Calculated coefficients for Ag and Pd (1.05 and 1.74, respectively) suggest that these elements should partition slightly into mss whereas actually they are hosted in pentlandite and iss. These anomalies also could be explained by the redistribution during the reaction of mss and residual liquid.

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## **Geology and Mineralization of the polymetallic (Ni+/-Cu, PGE) in the Birimian basement hosted in Ultramafic-Mafic intrusions, Guinea-Conakry**

by

**Mamady Cissé<sup>1</sup>, Xinbiao Lv<sup>2</sup>, Paul Robinson<sup>3</sup>**

Guinea is a West African coastal country with a landmass of 245.857 km<sup>2</sup> between lat. 7° and 13° N and long. 6° and 15° W. It is bordered on the west by the Atlantic Ocean and shares its border with six countries in the sub-Saharan region. Tectonically, it is located in the southern part of the Archean West African Craton (Birimian basement) and it has a mining potential similar to that of Western Australia. Guinea has rich and varied ore deposits with large bodies of high quality bauxite and iron ore, as well as gold and diamonds. Numerous geochemical anomalies, which are currently being explored, also suggest the presence of base metal deposits, such as nickel, copper, chromium, uranium, lead, manganese and graphite. For example, in the area centered at 9°21'00" W longitude and 9°34'00" N latitude, the Kèrouané NC-29-IX anomaly shows concentrations 850 ppm copper and 500 ppm nickel. These anomalies are hosted in crystalline schists within the Dabola Series over an area of 33 km<sup>2</sup>. Farther to the west in the Kissidougou area (NC- 29- VIII) located at 10°56'35 " W and 9°41'35 " N, another anomaly hosted an eluvial deposit of sulfurized pyroxenite and websterite has high concentrations of nickel (5000 ppm), copper (5000 ppm) , barium (1500 ppm), manganese (1000 ppm) and cobalt (200 ppm). These figures are based on exploration by the company AREDOR, ORG notice expl. Kissidougou and Kerouane (1994) and compiled by PAGEM (Projet Allemano-Guinéen d'Evaluation du Potentiel Minier, 1998) at a scale of 1: 200,000. More detailed exploration work needs to be carried out in the N'zerekore and Beyla prefectures, where there are mafic and ultramafic intrusions of undifferentiated age, and in the Youkounkoun and Kindia areas where there are indications of nickel and/or cobalt locally accompanied by chrome and copper. Using new exploration technologies it is likely that polymetallic (Ni+/-Cu, PGE) deposits of economic interest will be found in these areas. In my presentation I will document the current assessment of mineral resources in Guinea, discuss the geology of the various mineral districts.

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# **PGE mobilisation in subduction zones and implications for ore deposit formation**

by

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PGEs are interesting tracers of geological processes and of economic importance but their mobility in many environments is poorly understood. Subducted serpentinites have the potential to carry PGEs to great depths or transfer PGE to the sub-arc mantle upon devolatilisation. The sub-arc mantle is considered to be enriched in Pd and Pt relative to IPGE and therefore transport of these elements via high pressure fluids is deemed possible. However, PGE cycling in subduction zones is poorly understood. A combination of analytical techniques was used to trace the PGEs in serpentinites through the subduction cycle. Comparison of bulk PGE concentrations to primitive mantle and abyssal PGE concentrations provides an insight into large scale PGE transfer. Mineral mineral paragenesis work constrained the timing of sulfide growth (the major host of PGE), whereas LA-ICP-MS analysis determined the concentration of PGE hosted in sulfides in high-pressure serpentinites; high resolution feature mapping provided a method to detect PGM. The bulk concentrations of PGE in the subducted serpentinites are no different to PGE concentrations of primitive mantle and abyssal serpentinites. Therefore, these results indicate that no large scale transfer of PGE occurred, with the exception of slight Pd enrichment in two samples. Millimetre to centimetre scale mobilisation is proposed from sulfides to alloys and between sulfides. Sulfide PGE concentrations and sulfide parageneses provide complementary tools to assess redox conditions throughout the subduction cycle, which is vital to the oxidation state of the sub-arc mantle and hence the formation of arc-related ore deposits. An improved understanding of the geochemical behaviour of PGE could be applicable to the exploration of ultramafic hosted PGE and nickel sulfide deposits.

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## Channelling magma flow in the crust to form magmatic ore deposits

by

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Intrusion-hosted Ni-Cu-PGE magmatic sulfide deposits accumulate within crustal-scale magma networks that transport mantle-derived mafic and ultramafic magmas from mantle sources to the surface. Magmatic sulfide mineralization within such networks occurs in a variety of traps that form due to a combination of structural and fluid-mechanical processes. Ore-hosting structures include tubular chonoliths (e.g., Nebo-Babel and Limoiera), ribbon-shaped sills (e.g., Noril'sk and Nkomati/Uitkomst), funnel-shaped jogs within conduits (e.g., Voisey's Bay Ovoid), elongate funnel-shaped flares within dyke-like intrusions (Eagle, Tamarack), blade-shaped dykes (e.g., Expo-Ungava deposits in the South Raglan Belt) and near the bases of layered intrusions, which often comprise stacks of sills, adjacent to the entry points of feeder dykes (e.g., Voisey's Bay Eastern Deeps). Economic accumulations of magmatic sulfides in these settings are associated with channelized zones of high magma flux. Such mineralized zones make up a tiny fraction of the system as a whole, so it is clear that explorers need new tools and approaches to find new deposits. Although considerable research has been directed to the links between lithospheric architecture and Ni-Cu-PGE mineralization and the geochemical origins of the associated sulfide mineralization, far less work has focused on the physical processes involved in the transport of the host magmas, how and where high-flux channels develop in magma transport networks, and how and where sulfide liquids separate and accumulate to form high-value ore deposits.

Using a combination of theory and laboratory experiments, we examine the following four hypotheses that address these key questions: 1) Crustal-scale magma networks form by multiple transitions between dykes and sills, which are strongly controlled by pre-existing structures. This suggests that structural traps for ore, such as funnel-shaped dyke-sill transitions, are predictable; 2) Chonoliths and ribbons are preferred sites of mineralization and they form by a combination of (i) the development of mechanical instabilities at advancing dyke/sill fronts, (ii) thermal erosion of country rocks and consequent widening of flow pathways and (iii) concentration of magma flux through these pathways; 3) magma flow within established networks is periodic and varies spatially over time as a partially solidified network is reactivated by new batches of hot magma, leading to preferred linear channels within originally sheet-like bodies of flowing magma; 4) mineralization within magma networks occurs when the separation of dense Ni-Cu-PGE sulfide liquids occurs within channels, transient eddies and structural traps where magma flux is focused above a horizontal floor.

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# The Lago Grande Complex, Carajás Province, Brazil: insights into the remobilisation of Pd-Pt through post-magmatic, low-temperature oxidising fluids

by

Maria E. S. Della Giustina<sup>1</sup>, Hazel M. Prichard<sup>2</sup>, Cesar F. Ferreira Filho<sup>1</sup>, Iain McDonald<sup>2</sup>

The Lago Grande Complex (LGC) is a 2.76 Ga layered mafic-ultramafic intrusion located in the Carajás Mineral Province, Brazil, and is part of the PGE-enriched Serra Leste Magmatic Suit. The LGC is divided into an Ultramafic Zone (UZ), consisting of interlayered dunite, harzburgite and orthopyroxenite, and a Mafic Zone (MZ), comprising a sequence of gabbroic rocks. PGE-rich levels are located within the UZ. Three distinct associations are described in this unit, suggesting that different processes may have operated in the magma causing PGE concentration: i) within sulfide-poor chromitite layers, characterized mainly by IPGE-As-S phases and showing high Pt/Pd and low Pd/Ir ratios; ii) in sulfide-rich levels, with low Pt/Pd and high Pd/Ir ratios, and iii) in sulfide-chromite-poor intervals, with variable Pt/Pd ratios. Samples from the sulfide-bearing harzburgites and orthopyroxenites were selected for this study and reveal that at least three episodes of postmagmatic alteration has affected the LGC and promoted the re-equilibrium of the mineral assemblage, including the PGM. In the samples investigated, the igneous assemblage (Ol+OPX) is transformed into a diablatic association of cummingtonite+anthophyllite+chlorite and primary BMS is remobilised and recrystallised along with chlorite and also enclosing amphibole crystals, with an assemblage of Pn+Cp+galena+sphalerite. PGM were formed during this event and are mainly hosted at Pn grain boundaries or within hydrous silicates. This PGM assemblage consists mainly of Pd-Ni-As, Pd-As-Sb and Pd-Bi-Te phases, with minor sperrylite. Further post-magmatic alteration promoted sulfur-loss, transforming Pn to Mt and Cp into Bo, which is accompanied by a low-T silicate assemblage of antigorite+tacl. Pb is transferred into Pb-bearing PGM (Pd-Bi-Te-Pb and Pd-Pb phases) that crystallised chiefly within Mt or on Mt-silicate junctions and ZnS reacted to form a thin Zn-silicate rim on Mt borders. A final alteration episode is responsible for the transformation of Mt-to-Hem, probably due to redox reactions under low-T hydrothermal conditions. During this event, Pd was partially lost through the recrystallisation of Pd-Ni-As phases into maucherite (Ni<sub>11</sub>As<sub>8</sub>), a typical low-T hydrothermal mineral, and Pd-Bi-Te-Pb phases were, in turn, replaced by altaite (PbTe), which forms complex intergrowths with antigorite. Further studies on the sulfide trace-element signatures and sulphur isotopic composition are in progress and will provide additional clues to the Pd-Pt remobilization during postmagmatic, hydrothermal alteration. Moreover, they may reveal a link between the LGC and the world-class Au-Pt-Pd deposit of Serra Pelada, located a few kilometres to the north of the LGC

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## High-PGE Low-Sulphur Stratiform Mineralization in the Layered Northern Ultramafic Centre of the Lac des Iles Complex, Ontario, Canada

by

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The noritic Mine Block intrusion of the Archean Lac des Iles Complex in northwestern Ontario, Canada hosts the Lac des Iles palladium deposits that have been mined for over two decades. The northern part of the complex comprises layered ultramafic intrusions, some of which contain PGE occurrences with >1 g/t Pd+Pt. The best documented of these ultramafic-hosted PGE occurrences are the Sutcliffe Zone that consists of four subparallel, stratiform PGE-enriched horizons exposed within the Layered Series of Northern Ultramafic Centre. Field relationships, mineral paragenesis and lithogeochemistry indicate that two distinct types of cyclic units (CUA and CUB) exist in the Northern Ultramafic Centre. CUA-type cyclic units are interpreted to have formed from a Si-enriched parent magma. CUB-type cyclic units are inferred to have formed from a relatively Si-poor parent magma. The PGE-enriched horizons occur in four of the CUA-type cyclic units. In most of the cases PGE enrichment occurs near the top of the cyclic units in websterite and/or gabbro-norite. In one case PGE enrichment occurs halfway through the cycle in olivine websterite. The host rocks show weak to moderate hydrous alteration and are commonly found in association with disseminated and blebby sulfide mineralization (0.2-2 vol%); mainly pyrrhotite, chalcopyrite, and pentlandite with minor cubanite, troilite, and cobaltite. During hydrous alteration, the primary sulfides have been partially replaced by chalcopyrite, pentlandite, sphalerite, heazlewoodite, and chalcocite. Palladium occurs either in solution solid in fresh pentlandite and cobaltite or is associated with platinum group minerals (PGM).

In general the PGE-enriched horizons are associated with increases in total S, Cu and Zr contents and a decrease in Mg:Fe ratios of pyroxenes. They are characterized by PGE tenors averaging 643 ppm Pd+Pt (in 100% sulfide), Pd/Pt and Pd/Ir ratios ranging from 0.9 to 3.5 and 35 to 537 respectively, and a wide range of S/Se ratios (500-6000). The highest PGE tenors (4377 ppm Pd+Pt) are found in serpentinized olivine websterite having an average Pd/Pt ratio of 3.5 and a S/Se ratio of approximately 2,000. Mineralogical and geochemical evidence suggest that three processes were responsible for these PGE occurrences, viz.: (1) magmatic crystallization in which base metal and precious metals were concentrated in a sulfide melt, (2) a late-magmatic stage in which base metal and precious metals were concentrated in a volatile-rich fluid, and (3) a postmagmatic stage in which volatile fluids interact with early-formed assemblages resulting to the dissolution and redistribution of PGE.

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# Magmatic sulfide composition as petrogenetic and exploration tool: what have we learned from sulfide-rich pods in the atypical Lac des Iles Pd deposits (Ontario, Canada)?

by

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The Lac des Iles Pd deposits are atypical within the scope of platinum-group element (PGE) deposits. This is because the deposits do not resemble classical PGE deposits in a number of ways: the intrusion is small, concentrically zoned, and emplaced in a convergent setting; the ore zones are not stratiform, have very high Pd/Pt and Pd/Ir, and formed from andesitic magmas; the rocks have extremely variable textures and are irregularly altered. In addition to the disseminated sulfides, there are sulfide-rich pods present throughout the stratigraphy and in all rock types. The sulfide mineral textures and proportions within the pods vary from those that are essentially magmatic to those consisting predominantly of pyrite. We propose a model whereby sulfide liquids were concentrated into dilation zones prior to experiencing crystal fractionation. During subsequent alteration, pyrite replaced the primary mineralogy.

We have analyzed pyrrhotite, pentlandite and pyrite grains from the Lac des Iles sulfide-rich pods using LA-ICP-MS. In comparing our data with those from the literature, we noticed that trace element signatures of pyrrhotite and pentlandite derived from primitive magmas (ultramafic intrusions and flows, layered intrusions, and flood basalts) are different to those derived from more evolved magmas (andesites). The Ni-Cu-PGE deposits associated with primitive magmas typically occur within stable cratons or at rifted intraplate margins whereas the deposits associated with more evolved magmas typically occur in convergent or transpressive settings. Thus, the geochemical signature of pyrrhotite and pentlandite may be used to infer the nature and tectonic regime of their parental magma. Furthermore, we identified that the trace element composition and distribution of secondary pyrite from various Ni-Cu-PGE deposits are similar, suggesting a common ore-modifying process.

We also noticed that (1) pentlandite from PGE-dominated deposits is significantly enriched in Pd and Rh relative to pentlandite from Ni-Cu sulfide deposits; and (2) pyrite found in magmatic Ni-Cu-PGE deposits is enriched in Co and Se and depleted in Sb and As relative to pyrite found in low-temperature hydrothermal deposits. Thus, plots of Pd vs Rh in pentlandite and Co/Sb vs Se/As in pyrite appear to be effective at discriminating pentlandite from PGE-dominated and Ni-Cu sulfide deposits, and pyrite from Ni-Cu-PGE and hydrothermal deposits. In glacial deposits in large arctic/subarctic areas, pentlandite and pyrite can be recovered from the heavy mineral fraction. Therefore, the two plots that we developed can be used in exploration to fingerprint potential targets and adapt exploration strategies.

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# **An experimental study of metal partitioning between sulfide liquid and mafic, ultramafic melts: the importance of oxygen fugacity**

by

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Partitioning of metal elements between sulfide and silicate melts is important to understand the formation of magmatic ore deposits and especially metal enrichment in sulfides. Among all the parameters which can control this partitioning, oxygen fugacity is for sure one of the most important, because it could affect (i) the oxidation state of the metal element dissolved in the silicate melt, (ii) the content of S in the silicate melt, and (iii), the content of O in the sulphide liquid. As the partitioning is driven by an exchange reaction between sulphide and silicate melts, a variation in oxygen fugacity is likely to modify it.

A negative effect of oxygen fugacity on sulphide-silicate melt partitioning is indeed observed for Pt and to a lesser extent for Ni, Au and Pd, from literature data compilation. This effect is different for each element and is partially masked by the variability of experimental conditions and melt compositions. Previous authors described a correlation of the metal element partition coefficients between sulphide liquid and silicate melt ( $D_M^{sul-sil}$ ) with  $\log fS_2^{1/2} - \log fO_2^{1/2}$ , which suggest that both oxygen and sulphur fugacities play an important role in metal element partitioning. A coherent study is needed to differentiate the effect of these two parameters.

We will present high-pressure and high-temperature experiments in internally heated pressure vessels investigating the variations of the  $D_M^{sul-sil}$  of Ni, Cu, Co, PGEs, Ag and Au with oxygen and sulfur fugacities. A picrite and basalt from the Noril'sk region were used as starting materials. A homogeneous sulfide liquid segregated from the silicate melt during the experiments due to S addition, and was rapidly quenched at the end of the experiment. Sulfide droplets and silicate glasses were analysed by electron microprobe and laser ablation inductively coupled plasma mass spectrometry in order to determine partition coefficients for Ni, Cu, Co, PGEs, Ag and Au.

Our preliminary results corroborate the negative correlation between  $D_M^{sul-sil}$  and oxygen fugacity. We discuss how these variations could have affected sulfide compositions segregating from the magmas of the Noril'sk-Talnakh region. Recent works show indeed that the interaction with sedimentary rocks can strongly modify the redox state of Noril'sk magma, making it vary over a wide range of oxygen fugacities (see the abstract by Iacono-Marziano et al., this Symposium).

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# Carbonatitic melt in deep seated mafic pipes physically entrains dense sulfide blebs during vertical magma flow

by

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Unlike many elements that are concentrated in the continental and oceanic crust and can be recycled and redistributed through typical crustal processes, nickel, copper and the platinum-group elements are heavily partitioned into the core and mantle of our planet. However, mantle-derived melts associated with emplacement of mantle plumes or the development of arc-related magmatism have disturbed this segregated system, remobilising a portion of the metal content of the mantle and depositing large quantities of these elements in the crust in the form of Ni-Cu-PGE sulfides. The key elements missing from our understanding of these systems revolve around the poorly constrained fluid dynamics by which magmatic sulfide deposits are emplaced; specifically how immiscible sulfide liquids are transported and deposited within magmatic systems. We address this knowledge gap by investigating the field relationships as well as the minero-chemical, isotopic and morphological features of sulfide blebs hosted in a mantle-derived volatile-rich alkaline mafic pipe that intruded the lower continental crust of the Ivrea Zone of northwest Italy. The <300m-thick pipe is composed of a matrix of subhedral to anhedral amphibole, phlogopite and orthopyroxene that enclose sub-centimeter-sized grains of olivine. The 1-5m-wide rim portions of the pipe locally contain significant blebby and disseminated Ni-Cu-PGE sulfide mineralization. Three-dimensional high-resolution X-ray computed tomography analyses indicate that beside a cotectic-like family of smaller (<1-2 mm) and rounded intra- and intergranular sulfide blebs, largely made up of pyrrhotite±pentlandite, the pipe also contains a population of larger blebs (5-50 mm), with a core commonly made up of pyrrhotite and rims comprising pyrrhotite±pentlandite±chalcopyrite±mackinawite±cubanite and platinum-group element minerals. The morphology of the larger blebs reveals the presence of embayments and protrusions, in and around which a halo of sulfide myrmekites and patches of magmatic dolomite and calcite commonly reside, displaying intergrowth features that indicate wetting behavior between carbonates and sulfides. From a sulfur isotope point of view, the small blebs and the larger aggregates are not systematically different, with overlapping  $\delta^{34}\text{S}$  signatures ranging between 1.03‰-1.96‰. Furthermore, preliminary experimental results confirm the preferential association of carbonate and sulfide liquids in the presence of silicate crystal mush. We put forward the new hypothesis that upon emplacement at the base of the crust, sulfide-saturated mantle-derived magmas originating from the metasomatised lithospheric mantle may exsolve a carbonatitic liquid, which could wet and physically entrain sulfide blebs. These could coalesce forming much larger aggregates during ascent of the silicate magma.

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## **PGE, Cu and Ni behaviour in regolith from the Sub-Saharan Dablo PGE-Ni-Cu project, Burkina Faso**

by

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PGE-(Ni-Cu) element mobility in regolith has previously been described only over Ni laterite deposits. In this contribution we will examine PGE, Ni and Cu mobility in the regolith overlying the Dablo Main ultramafic to mafic intrusion (“DMI”) located in north central Burkina Faso. This area is typically dry and hot but experiences a brief but intense wet season once per year causing widespread flooding. The DMI is 6 km in strike length, up to 500 m wide, and is oriented at 020 degrees. It is part of a cluster of mafic and ultramafic intrusions of early Birimian age intruding into metasediments with minor volcanics of the Bouroum greenstone belt.

The DMI is host to a PGE-(Ni-Cu) occurrence found on outcrop in 2011 by Newgenco Pty Ltd that was subsequently drilled in 2014. This drilling encountered several sulfide-bearing horizons that were PGE, Ni and Cu bearing. Through surface exploration, the DMI was found to be strongly PGE anomalous for its entire length. Since 2014, auger and air core (AC) drilling was completed in order to get through the regolith and obtain bedrock samples. The geochemical profiles discussed in this presentation are from the AC regional drilling over the DMI.

Overall the regolith profiles were found to be very variable with major differences between the northern and the southern areas covering the DMI. The regolith profiles in the northern area is usually less than 10 m thick and is composed of very thin chocolate covered soils (typically <3 m.), saprolites and saprocks. The regolith in the central and southern areas are thicker (10-20 m.) and composed of soils/duricrusts, local Fe rich saprolites to transitional limonites, saprolites and saprocks.

Profiles for the regolith over the northern DMI (where mineralization is known) have lower PGE contents with respect to those in the bedrock. In contrast in the Southern DMI area, high PGE, Cu and Ni contents were obtained in the regolith with respect to the bedrock. PGE associates with high concentrations of Fe, Mn and residual Cr at several levels within the regolith. When Fe-enrichment is absent, the PGE's are not enriched in the regolith.

Erosion by floods/water course in the northern section likely removed any overlying Fe-rich regolith. Consequently, the regolith environment must be clearly understood prior to any interpretation of surficial (soil) data and geochemical dispersions.

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## Digital rocks: switching from 2D and 3D observation to 3D quantification

by

Bélinda Godel\*

X-ray computed tomography (XCT) was originally developed and used as a medical imaging technique. It is a non-destructive technique that allows the exploration of the internal structure of solid objects in 3-D. The range of X-ray energies used allows the X-ray to be transmitted through complex and dense materials including ores of various types. XCT is now commonly applied to a wide variety of rocks across a range of scale (from 100's meters down to <1 micrometre) and it provides a unique mean at creating digital rocks that are used for 3D quantification and modelling using dedicated workflows and algorithm. Although, digital rocks is a common practice in the oil and gas industry to help in the assessment of reservoir quality, its adoption to characterize and quantify in 3D Ni-Cu-PGE ores in particular remains fairly limited. For ore materials, low resolution data (i.e. millimetre range) can be acquired on samples varying in size from tens of centimetre up to entire drill core length using conventional medical CT scanner. This type of scanner allows to record the data rapidly (several meters of drill core per hour) but the absence of X-ray source filter, the range of energy used and the spatial resolution achievable limit the ability to differentiate complex mineral assemblage. Hence it only gives a broad overview of ores and is best used to quantify parameters that will complement geological logging (i.e. direct density logs, fracture networks, layering, breccia zones, ore heterogeneities etc.). In most cases, high-resolution X-ray computed tomography data have to be acquired on a subset of sample (up to ~5 cm in diameter and ~10 cm in length) to allow mineralogical quantification in 3D. Recent scanners have the ability to generate multi-scale (25 down to 0.3  $\mu\text{m}$  voxel size) imaging of a given sample. The wide range of voltage, current, power, filters, source and detector position combinations possible with modern scanners allow to scan a wide range of material for mineral system studies at high resolution. When combined with dedicated workflows and algorithms, the results generated benefit from mineral exploration through to ore behaviour prediction during downstream processing. This contribution will illustrate some of the latest 3D quantification and applications to Ni-Cu-PGE ores.

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## **Mafic dykes and sills of the Capricorn Orogen (Western Australia)**

by

**Bélinda Godel<sup>1</sup>, Sarah-Jane Barnes<sup>2</sup>**

Extensive mafic dykes and sills intruded within the Paleo- to Neo-proterozoic sedimentary basins within the Capricorn Orogen of Western-Australia and extends over a distance of 1300 km forming so-called large igneous provinces (LIP). The mafic sills and dykes have recently been classified into six different intrusive suites by the Geological Survey of Western Australia: (i) the Waldberg dolerite intruding at ~1515 to 1500 Ma; (ii) the Narimbunna dolerite intruding at ~1465 to ~1450 Ma and; (iii) and (iv) the Kulkatharra dolerite sills and the Capricorn Range dykes both intruding at ~1070-1080 Ma; (iv) the Mundine Well dykes intruding at ~765 Ma and the (vi) Minga Well dolerite dykes those age remain unconstrained. To date, no detailed assessment of the Ni-Cu-PGE exploration potential of these mafic dykes and sills has been carried out and only a limited number of Pt and Pd analysis are available. New sulphur, PGE and Au data were collected on the mafic dykes and sills intruding in the Capricorn as part of this study. These new data are combined with existing major and trace element data and a range of igneous petrology and geochemical modellings over a range of pressure and temperature to assess in detail the potential for the different sills and dykes to host (or be involved in the formation) of Ni-Cu-PGE mineralization within the Capricorn Orogen. The Waldberg and Narimbunna dolerite sills are considered to be of limited interest for Ni-Cu-PGE exploration due to sulfide saturation episode(s) occurring prior to their final emplacement into the upper crust. In contrast, the Capricorn Range dykes and the Kulkatharra dolerite sills are fertile in term of Ni, Cu and PGE and are similar in term of compositions and mantle sources to the Alcurra dyke suite cropping out in the WestMusgrave. These new results confirm geochronological and paleo-magnetic data and highlight the homogeneity of the mantle source over a large lateral extend at ~1070-1080 Ma. Although, only a limited number of samples from the Mundine Well and the Minga Well dolerite dykes have been analysed, the results on few samples highlighted several interesting geochemical features.

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# **Evaluation of PGM as potential index mineral assemblages for high grade Cu-PGE deposits in the Coldwell Alkaline Complex, Canada**

by

**David J. Good<sup>1</sup>, Doreen E. Ames<sup>2</sup>, and Louis J. Cabri<sup>3</sup>**

The results of a comprehensive study of platinum group minerals within 4 mineralised zones at 3 Cu-PGE deposits in the 1.1 Ga Coldwell Alkaline Complex are characterised with respect to the widely varying mineralisation styles to test the hypothesis that certain PGM assemblages are unique to the highest grade deposit type and could act as index minerals for exploration.

The Area 41 and Two Duck Lake gabbroic intrusions are located 16 km apart at the north and east margins of the complex, respectively, whereas the Geordie Lake deposit is located near the centre of the complex. Each intrusion is believed to have formed by multiple pulses of co-genetic magma. In general, the mineralisation at each deposit consists of disseminated chalcopyrite  $\pm$  pyrrhotite  $\pm$  bornite, but each zone exhibits a distinctive mineralisation style and Cu/S, Cu/Pd, Pd/Pt and Pd/Ir that can be related to the magmatic processes acting within the respective intrusive setting.

Heavy mineral separates were prepared from large samples by hydros separation of pulverised material; or by electric-pulse disaggregation and panning of <1 kg drill core specimens, to obtain statistically significant collections for each deposit. The separates were sieved and mounted on a total of 27 sized monolayer polished sections and the platinum group minerals were identified by automated SEM-EDS techniques and verified manually. The sum of measured surface areas for each mineral was calculated to provide estimates of relative mineral abundances.

A total of 768 precious metal grains (in 32 species) were identified at the Main zone (Marathon deposit); 48 grains (12 species) at Geordie Lake; 526 grains (46 species) at Area 41; and 9493 grains (47 species) at W Horizon (Marathon deposit). The PGM common to all deposits include Pd-arsenides, Pd antimon-arsenides and sperrylite. The W Horizon is distinguished by the presence of Pd and Pt sulfides, Pt sulf-arsenides, Pt telluride, Rh-bearing Ni-Fe sulfides, ruarsite, laurite, Pt-Fe alloys and a rare unknown Pd-Ge alloy.

There is a relationship between PGM species and Pd enrichment as indicated by the range for Cu/Pd. For instance, the Main zone and Geordie Lake samples have mantle-like Cu/Pd (1750-10400) and contain the fewest number of PGM species. On the other hand, the PGE enriched W Horizon (up to 53 ppm Pd + Pt over 8 meters) and Area 41 deposits have very low Cu/Pd (80-910) and contain the most diverse assemblages of PGM including several possible index minerals.

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## **The Gabbro-10 massif with Fe oxide and PGE mineralisation in the Monchegorsk layered complex (Russia): new data on whole-rock chemistry**

by

**Groshev N.<sup>1</sup>, Malygina A.<sup>2</sup>**

The Monchegorsk Layered Complex (MLC) is a mafic-ultramafic intrusion containing numerous PGE-Ni-Cu-Cr-V deposits and occurrences. The range of metals hosted by the intrusion is comparable with the Bushveld Complex. Despite on a long prospecting and mining history of the intrusion an origin of many Monchegorsk deposits remain unclear. It is particularly true for PGE and Fe-oxide mineralisation known within the Gabbro-10 (G-10) massif (Voytekhovich et al. 2002; Efimov et al., 2004; Pripachkin et al., 2015). Two detailed borehole logs of the representative NW-SE cross-section of the G-10 and 18 XRF analyses were made in this study. These first results contribute to define a primary mineral composition of rocks, to evaluate an origin of the G-10 unusual rock association and to constrain a genesis of its PGE and Fe-oxide mineralization.

The G-10 massif (“gabbro of 10th anomaly” target) is situated at the south part of the MLC. Whole-rock data shows that porphyraceous gabbroid corresponds to the MLC’s melanocratic norites (19-20 wt. % MgO, 69-80 mol. % norm-An), which has elevated Cr content. Sheared hybrid gabbro with 6-7 wt. % MgO and 58-66 mol. % norm-An has intermediate composition between melanorite and basement rocks. Gabbro has a composition close to the Monchetundra gabbro-norites (3-4 wt. % MgO, 48-59 mol. % norm-An). Two whole-rock analyses have shown that diorite is actually felsic rock of granodioritic composition (66-69 wt. % SiO<sub>2</sub>, 1 wt. % MgO, 11-21 mol. % norm-An), which is very similar to granophyres of the Imandra lopolith (Fedotov et al., 2004).

Considering these data we suggest following preliminary conclusions. The G-10 massif is a sill-like body formed probably as a result of three magmatic events, comprising an intrusion of high-Cr melanoritic melt with composition close to the MLC’s parent magma, a consecutive intrusion of a gabbro-noritic magma (comparable with Monchetundra or Vurechuaivench gabbro-norites) and, finally, a felsic intrusion appeared due to partial melting of the basement. PGE mineralisation of the studied section occurs at the contact of high-Cr magma with the basement rocks (contact style) and within sheared zones in the basement (offset style). Fe-oxide mineralisation is obviously connected with granodiorite intrusion and was likely formed due to gravitational accumulation of magnetite in a felsic melt.

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# **Lumping geochemically-defined ore types in drill holes for simplified 3D modelling: an example from the Kevitsa Ni-Cu-PGE orebody, Finland**

by

**E. June Hill<sup>1</sup>, Steve J. Barnes<sup>1</sup>, Margaux Le Vaillant<sup>1</sup>**

A 3D geology model is a simplified version of the true geology, designed to give a visual summary of the geometry and distribution of major geological elements in a specified region. Drill holes provide detailed data of the subsurface that can be classified into geological units that are the fundamental elements of the 3D model. Generally, lumping is required to reduce the number of geological units in the drill holes prior to model building. Lumping is a subjective process, which means that different geologists will lump in different ways and will typically not record the rationale behind their decision; this means the “experiment” is not reproducible. We have developed a method of lumping geological units, in this case based on assay data, using a continuous wavelet transform and tessellation (cwt-tess). This method reduces subjectivity and can easily be repeated (e.g. on an updated or new drill hole) by using the same parameters, ensuring that the lumping process is consistent over all drill hole data.

The Kevitsa Nickel-Copper-PGE disseminated sulfide orebody is hosted in a Proterozoic layered intrusion in northern Finland. Internal geological subdivision and correlation within the intrusion is very difficult to do consistently from lithological observations, owing to general homogeneity of rock types and an overprint of alteration, but distinct variability is evident in Ni and PGE sulfide tenors. In its raw form, the tenor variation data set appears noisy and unsystematic. We have applied the cwt-tess method to classifying ore types based on tenor variations, expressed as transformed log-normalised ratios of Ni/S and Pd/S, consistently and objectively reducing the number of units in each drill hole to create a simplified 3D model of the orebody. Our results reveal shallow inward dipping cryptic layering entirely defined by sulfide composition, reflecting an increase in Ni and PGE tenor with time during emplacement of the sulfide-bearing cumulates. We interpret this as a progressive increase in silicate-sulfide mixing efficiency as the intrusion developed from an interconnected sill sediment-complex choked with country rock inclusions into a freely convecting magma chamber. Based on this case study, we show that the cwt-tess method can add considerable value by distinguishing the wood from the trees in large 3D geochemical databases. The method may be widely applicable in other Ni-Cu-PGE deposits where tenor variations appear at first sight to be chaotic and uninterpretable.

We thank First Quantum Minerals Ltd for access to the Kevitsa mine database.

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# **Diversity of Ni-Cu-PGE mineralization and emplacement of the Black Thor-Double Eagle intrusive complexes of the Ring of Fire intrusive suite in the McFaulds lake greenstone belt, Oxford-Stull domain, Superior Province, northwestern Ontario, Canada**

by

**Michel G. Houlié<sup>1\*</sup>, C. Michael Lesher<sup>2</sup>, Riku Metsaranta<sup>3</sup>, Vicki McNicoll<sup>4</sup>,  
Heather Carson<sup>2</sup>, and Naghmeh Farhangi<sup>2</sup>**

One of the most prominent features of the Meso-Neoproterozoic McFaulds Lake greenstone belt (MLGB) within the Oxford-Stull domain (OSD) of the Superior Province (Canada) is the abundance of mafic-ultramafic intrusions. The intrusions contain a wide variety of orthomagmatic mineralization styles, including world-class Cr deposits, a major Ni-Cu-(PGE) sulfide deposit, and numerous Fe-Ti-V prospects. At least two generations of mafic-ultramafic intrusions (ca. 2808 and 2734 Ma) appear to host the mineralization, although the bulk of significant mineralization appears to be associated with Neoproterozoic intrusions.

The Mesoarchean Fishtrap-Highbank intrusive complex (ca. 2808 Ma) occurs along the southern margin of the OSD near the margins of an older crustal block (Mesoarchean core of the North Caribou Terrane), whereas Neoproterozoic intrusions occur predominantly in the central part of the OSD. This spatial and temporal distribution of mafic-ultramafic intrusions suggests that the OSD records multiple episodes of intracontinental rifting, in which Mesoarchean intrusions might represent early phases, whereas Neoproterozoic intrusions might represent later phases. The Neoproterozoic intrusions, referred collectively as the Ring of Fire intrusive suite (RoFIS), exhibit incredibly consistent U-Pb crystallization ages at ~2734 Ma, indicating a large mafic-ultramafic event that can be further subdivided into two main magmatic sub-suites: an ultramafic-dominated (e.g., Black Thor (BTIC) and Double Eagle (DEIC) intrusive complexes) and a mafic-dominated.

The BTIC and the DEIC are relatively large elongate komatiitic intrusions exposed over a combined strike length of about 15 km, with thin upper mafic parts and thicker lower ultramafic parts that host Cr and several types of Ni-Cu-(PGE) mineralization including: (1) conduit-style mineralization within feeder systems (e.g., Eagle's Nest), (2) contact-style mineralization along the basal margins of the intrusions, and breccia-style mineralization associated with a cross-cutting but coeval websterite intrusion. The wide diversity of Ni-Cu-(PGE) mineralization styles hosted within these complexes supports the dynamic nature of this flow-through system and the generation of sulfide-oxide mineralization over the complete lifespan of this magmatic system. This is reflected in the presence of early-magmatic, Ni-Cu-(PGE) mineralization within the conduit and along the basal contact; intermediate-magmatic Cr mineralization within the chromitite horizon, and late-magmatic Ni-Cu-(PGE) mineralization associated with magmatic breccias.

The regional distribution and metal endowments of Neoproterozoic mafic-ultramafic intrusions exceed, by far, those of Mesoarchean intrusions in the OSD. This observation suggests that unlike the models for many other districts, it was later phases of mantle-derived magma emplacement farther away from intracratonic discontinuities that were more productive in generating significant Cr-(PGE), Ni-Cu-(PGE), and Fe-Ti-V mineralization than earlier phases emplaced along intracratonic margins.

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## **News from the Bushveld: The world-class Waterberg PGE deposit, Limpopo Province, South Africa**

by

**F. M. Huthmann<sup>1</sup>, M. A. Yudovskaya<sup>1,2</sup> and J. A. Kinnaird<sup>1</sup>**

The Northern Lobe of the 2.06 Ga Bushveld Complex differs from the Eastern and Western Lobe of the complex with which it may be connected. Its basal, pyroxene-dominated Platreef is one of the worlds largest and most valuable deposits of platinum-group elements and associated significant Ni and Cu reserves. Recently Platinum Group Metals (PTM) have intersected mineralized mafic rocks tentatively interpreted to be of Bushveld affinity in drill core north of the interpreted end of the Northern Lobe. Since the discovery in 2011 extensive drilling has confirmed a >3.5 by 24 km lobate intrusion overlying basement rocks and itself covered by Paleoproterozoic sediments of the Waterberg Group. Whereas the Northern Lobe is located in the stable Kaapvaal Craton, the Waterberg Project is located in the Southern Marginal Zone of the Limpopo Complex which may expose it to a level of Paleoproterozoic tectonism not previously observed in the Bushveld Complex.

The mafic succession consists of the so-called Upper and Main Zones (UZ and MZ) resting on Archean gneiss and granofels. The UZ is composed of ferrogabbro and ferrogabbro-norite, however it lacks the magnetite typically observed in the Northern Lobe. Below the UZ, the putative MZ is composed of gabbro-norite, transitioning into an ultramafic zone composed of troctolites and harzburgites. Recently acquired age dates for these rocks are within error coeval with published ages for the rest of the Bushveld Complex.

Mineralisation occurs in two zones located in the putative upper (T-Zone) and lower Main Zone (F-Zone), respectively. The mineralisation is 3 to 60 m thick and has so far been intersected along 17 km of strike. Both zones are Pd-dominated with unusual amounts of Au in the T-Zone. Sulfides comprise pyrrhotite, chalcopyrite and pentlandite with platinum group minerals. The current resources at the Waterberg Project consist of 246 Mt at 3.25 g/t 3E (Pt+Pd+Au) inferred and 121 Mt at 3.24 g/t indicated. High-grade zones with <14 g/t 3E over >10m may occur.

We present new data and interpretation for this newly discovered deposit, its highly mineralised ore zones and emplacement history. Detailed whole rock, 6 PGE and logging data sheds light on the similarities and differences of this project and the “old” Platreef mineralisation.

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# How to produce massive sulfide deposits by magma-sediment interactions: the Noril'sk-Talnakh case-study

by

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Most of the intrusions in the Noril'sk-Talnakh region (Siberia) are hosted in a thick sedimentary sequence, including abundant evaporitic and terrigenous rocks. Three over at least 22 mafic-ultramafic intrusions in the region have unusually thick massive sulfide deposits (up to 45m). This important S enrichment, together with anomalously variable and high isotopic composition of S, strongly suggests a contribution from sulfate-bearing host rocks. Here we present the effects of sulfate assimilation on mafic-ultramafic magmas and discuss the combined assimilation of evaporitic and carbonaceous rocks as a mechanism to generate massive sulfide deposits.

Interaction experiments were conducted at conditions relevant to the emplacement of Noril'sk type intrusions (1200 °C, ~80 MPa) to simulate the assimilation of sulfate and/or organic compounds by ultramafic magmas. We used a picrite from Noril'sk1 intrusion, coal and anhydrite from the area.

We also employed gas-melt thermodynamic calculations to quantify the effect of these assimilations on the redox conditions and the S content of the magma. We investigated the role of temperature, pressure, and initial gas content of the magma in the assimilation process, in order to match possible emplacement conditions of Noril'sk, Talnakh and Kharaelakh intrusions.

Both experimental and modeling results indicate that the incorporation of sulfates into the magma increases its sulfur content, but also oxidises it, suppressing sulfide saturation and olivine crystallisation. Extreme assimilations lead to sulfate saturation in the magma. Conversely, the interaction with carbonaceous sediments induces a strong reduction of the magma, even for extremely low degree of assimilation, and promotes sulfide segregation and magma crystallisation.

The thermodynamic modeling clarifies and quantifies the effect of anhydrite or coal assimilation on the redox state of the magma, only qualitatively illustrated by the experiments.

Our study shows how high-temperature interactions between mafic and ultramafic magmas and evaporitic or organic matter-bearing rocks lead to a dramatic change in the redox state of the magma and its volatile content. The application to the Noril'sk-Talnakh district suggests that massive sulfides could have resulted from (1) S incorporation into the magma by assimilation of sulfates, followed by (2) a substantial reduction of the magma due to assimilation of carbonaceous sediments. If one of these two steps did not occur, or the assimilation was not large enough, massive sulfides were not segregated. We conclude that exceptional conditions favouring an important assimilation of sediments are needed to form exceptional ore deposits like those of the Noril'sk-Talnakh district.

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# The Windimurra Igneous Complex: an Archean Bushveld?

by

Ivanic, T.J.<sup>1</sup>, Nebel, O.<sup>2</sup>

The Archean Youanmi Terrane of the Yilgarn Craton hosts four massive suites of mafic–ultramafic layered intrusions and sills. These igneous bodies provide a unique window into Meso-Neoproterozoic magmatic processes and mantle composition, and may host significant economic deposits. The largest of these is the plume-related and laterally extensive 2.81 Ga Meeline Suite, a predominantly anhydrous, tholeiitic suite comprising five layered mafic–ultramafic intrusive complexes 25–85 km in long dimension. These intrusions host significant V–Ti mineralization in their fractionated, Fe-rich Upper Zones, marking their economic significance. Recent mapping, combined with aeromagnetic, gravity and seismic surveys has provided unparalleled 3D constraints on the largest of these intrusions, the Windimurra Igneous Complex. The results of 3D modelling show that the Complex is thicker than previously recognised. At approximately 11 km, it is the thickest layered mafic–ultramafic intrusion identified globally and one of the largest such intrusions volumetrically. The Complex consists of eight distinct components including a thick layered series of four stratified cumulate mineral zones. The zone stratigraphy and many other features associated with this Complex share great similarity to those identified in the well-studied Bushveld Complex, South Africa. On a large scale, three discordant units are delineated geometrically, providing fundamental constraints on a multi-stage genetic model for magma emplacement in this Complex. The Complex is divided along the Shephards Discordant Zone into an eastern lobe with four zones and a cross-cutting western lobe with at least three zones. The Upper Zone of the western lobe is modelled as a shallow-dipping sheet-like body, which cuts down into Middle Zone rocks. The Roof Zone and Kanti Murdana Volcanics Member occur as cross-cutting plutons and roof pendants, respectively. The indication of a thick, subsurface Ultramafic Zone in both the Windimurra and neighbouring Youanmi Igneous Complexes provides a potential target for Ni–Cr–PGE mineralization. These features, combined with a 1:200,000 scale interpreted bedrock geology map for the Youanmi Terrane intrusions led us to conclude that the Meeline Suite as a whole is an intrusive Large Igneous Province with an estimated volume second only to the Bushveld Complex.

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## Tracking down chromitite-hosted PGE behaviour and source(s) for the Windimurra Igneous Complex

by

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The Windimurra Igneous Complex is the thickest layered mafic–ultramafic intrusion identified globally and the largest in Australia. It is part of the plume-related and laterally extensive Meeline Suite, a 2.81 Ga large igneous province. The Complex shares many similarities to the Bushveld Complex in South Africa, and is divided into two lobes of stratiform cumulate mineral zones of the layered series: Ultramafic, Lower, Middle and Upper Zones, and volumetrically smaller marginal Border Zone, a series of discordant pipes and a Roof Zone. So far, economically significant mineralization is present in the fractionated, Fe-rich Upper Zone (V–Ti). However, discovery of a thin chromitite horizon with PGE sulfides within the Lower Zone has been cause for speculation on whether the Complex may host an abundance of Cr–Ni–PGE mineralization at depth. The indication of a thick, subsurface Ultramafic Zone in seismic data has changed the interpreted character of the Complex from a high-Ca–Al (anorthositic) body to a more typically tholeiitic or high-Mg tholeiitic affinity, similar to the Bushveld. Petrography, augmented by 3D CT scanning of a sample of the chromitite horizon, reveals ‘egg carton’ geometry on a 20–100 mm scale. The horizon shows cross-cutting relations relative to host rock cumulate layering on a metre scale in outcrop. We interpret this to be a result of perturbation on the floor of the magma chamber during accumulation of the Lower Zone triggered by small-scale but high-temperature melt influx. Whole rock PGE data from this chromitite, ultramafic rocks with disseminated chromite and other gabbroic rocks from the Complex record selective PGE-concentrating events during repeated magma recharge. Platinum concentration varies locally (Pt/Pd<1) with up to 19 ppb in cumulate lithologies, ~760 ppb in gabbroic pegmatites and ~3150 ppb in the chromitite seam. These data will be complemented by Re–Os data to assess source/age characteristics. Magma chamber processes were locally conducive to chromitite formation which is, in the example studied, strongly correlated to elevated PGEs. On a small-scale, this horizon shows some features of a miniature-reef and we will further examine sulfide distribution across this layer in 3D. Our PGE data show suprachondritic P–PGE/I–PGE patterns, which is consistent with magma chamber recharge from a source, which is undepleted in P–PGE. Hence this location could be among other mineralized horizons, and/or above an elusive and yet unidentified ‘Critical Zone’ between the known extent of the Lower Zone and the unexposed, approximately 3 km thick Ultramafic Zone beneath.

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# **Mafic dike-hosted Ni-Cu-Co-(PGE) mineralisation of the former mine « Bergsegen », Sohland/Rožany, Germany/Czech Republic**

by

**Tom Járóka<sup>1</sup>, Thomas Seifert<sup>1</sup>**

The magmatic Ni-Cu-Co-(PGE) occurrence of Sohland-Rožany [DE/CZ] is located about 50 km E of Dresden (Saxony/Germany) in the Lusatian Highlands. It is associated with a 390-350 Ma predominantly WNW ESE striking mafic dike system, outcropping in an area of 40 x 30 km and hosted by Cadomian granitoids of the Lusatian Block (Bohemian Massif). SEM-MLA studies reveal an amphibole-gabbro-noritic to amphibole-gabbroic composition of the Sohland-Rožany dike (10-20 vol.% plagioclase, 5-30 vol.% orthopyroxene, 10-30 vol.% clinopyroxene, 20-30 vol.% amphibole, 5-15 vol.% chlorite). Bulk geochemistry of barren gabbro-norite (45.74 wt.% SiO<sub>2</sub>, 12.73 wt.% MgO, 14.36 wt.% Fe<sub>2</sub>O<sub>3</sub>(T), Mg# 50 and 0.1 wt.% S) shows elevated Ni + Cu contents (472 ppm Ni, 184 ppm Cu, 74 ppm Co, 540 ppm Cr), while Au + PGE (4 ppb Au, 3.2 ppb Pt, 3.5 ppb Pd) are not enriched.

Larger sulfide accumulations within the small-scale Sohland-Rožany dike intrusion (1.5 km strike length, 5-20 m width) were discovered in 1900 during well constructions. They were mined in an underground operation from 1901-1920 (20 kt ore @ 2-4 wt.% Ni, 1-2 wt.% Cu and 0.1 wt.% Co). At least 4 different ore types can be distinguished in dump samples from the former Ni-Cu-Co mine “Bergsegen” of Sohland-Rožany: (I) pyrrhotite-dominated disseminated ore (< 10 vol.% sulfides; pyrrhotite > pentlandite > chalcopyrite), (II) chalcopyrite-dominated disseminated ore (< 5 vol.% sulfides; chalcopyrite > pyrrhotite > pentlandite), (III) massive pyrrhotite-pentlandite ore (> 50 vol.% sulfides; pyrrhotite > pentlandite > chalcopyrite) and (IV) chalcopyrite-plagioclase veins (> 30 vol.% sulfides; chalcopyrite >> pyrrhotite).

Bulk geochemical analyses from previous studies indicated only a low PGE + Au tenor for the different ore types (max. 200 ppb PGE, max. 150 ppb Au). However, our SEM-EDX analyses show that all ore types contain small amounts of PGMs, whereas Pd-Ni-Bi tellurides of the melonite-merenskyite series are the most prominent. Michenerite and testibiopalladite can be observed subordinately. Pt-dominated PGMs are represented by sperrylite. The highest PGM amounts are obviously associated with the disseminated and massive pyrrhotite-dominated ore types. Besides the PGMs native gold, electrum and Ag-, Bi-, Ni- and Pb-tellurides were also identified. PGMs and tellurides (both with grain sizes < 25 µm) are often localised at sulfide-silicate grain boundaries. They also occur in pyrrhotite, pentlandite, violarite and more rarely in silicates.

A replacement of pentlandite by violarite, the PGM distribution and a considerable alteration of the rock-forming silicates suggest a late-stage magmatic-hydrothermal overprint of the mineralization.

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## Platinum and Palladium Minerals in the Sulfide Globules from the Trill Offset Dike, Sudbury, Canada

by

Valery Kalugin<sup>1</sup>

Sulfide globules of 3-12 mm in diameter have been found in the quartz diorite of the Trill Offset dike to the west of the Sudbury Igneous Complex. They have a well-defined zoning with a pyrrhotite core and chalcopyrite rim. There are pyrite, magnetite, smythite, silicate minerals and lamellae of chalcopyrite and pentlandite in the pyrrhotite of the core. Each globule is surrounded by a halo (0.5 - 1 mm in thickness) consisting of numerous small grains of chalcopyrite. The globules were formed from the droplets of the immiscible sulfide liquid transported by the silicate melt during the dike formation. The halo seems to be the result of the escape of the fluid from the sulfide liquid under cooling.

The aim of the study is to identify minerals of the platinum group (MPG) in the globules and understand the behavior of platinum group elements (PGE) in the crystallization and subsolidus transformation of the sulfide ore. The SEM of Tescan Mira 3 with the EDS Oxford X-Max 80 and the microprobe analyzer of CamebaxMicro were used.

Seven species of MPG and Au-Ag alloy were detected. Tellurides of Pt and Pd are most abundant. Merenskyite, moncheite, michenerite, and kotulskite occur as individual grains or intergrowths of 2 to 4 minerals in form of lamellae in each other. According to experimental data, the quenching temperature of the coexisting merenskyite, michenerite and kotulskite in the globules can be higher than 489 °C. Furthermore, moncheite forms individual grains and intergrowths of two phases of moncheite-insizwaite solid solution. Platinum arsenides are represented by sperrylite of two types. The first form the small partially dissolved inclusions in the tellurides and contain the impurity of Sb. The second form the individual faceted crystals without impurities.

Minerals of Pd with antimony, tin, and arsenic are rare. These are mertieite-I ( $\text{Pt}_{10.84}\text{Cu}_{0.17}$ )( $\text{Sb}_{3.55}\text{As}_{0.44}$ ) and unknown phase with the formula of  $\text{Pd}_{10.97}(\text{Sn}_{2.09}\text{Sb}_{0.51}\text{As}_{1.43})_{4.03}$ . They were found in the intergrowths and perhaps they belong to the solid solution.

MPG are found in all parts of the globule. Many of them are located inside the silicate inclusions. A slight enrichment of MPG observed in chalcopyrite rim and in the halo. Most of the MPG were formed as a result of the decomposition of the sulfide solid solutions. Due to the fluid transport, PGEs were removed from the ore-forming sulfides and deposited in the silicate inclusions and in the halo.

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# Geochemical characteristics of Cu-Ni-PGE mineralisation at the Manchego Prospect, Musgrave Province, Western Australia: Implications for exploration

by

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The abundance of mafic-ultramafic layered intrusions in the late Mesoproterozoic Giles Complex of the Musgrave Province results in one of the most prospective areas for magmatic sulfide mineralisation in the world. Especially the discovery of a large Ni-Cu-PGE deposit at Nebo-Babel in 2000 triggered enhanced exploration in the region. More recently, a number of low-grade prospects were identified across the Musgrave Province. The most significant is an occurrence of massive to disseminated sulfide mineralisation reaching up to 0.6 wt % Cu, 0.5 wt % Ni and 1 ppm Pt + Pd at the Manchego Prospect.

Manchego was initially identified from a Spectrem airborne electromagnetic survey at the intersection of two linear, positive magnetic anomalies interpreted to represent sill-like intrusions. Drilling confirmed the presence of massive to disseminated sulfides along two gently dipping zones of up to 25 m in thickness. The mineralisation is hosted by a range of gabbro-noritic rock types situated below a linear magnetic anomaly interpreted to be a magnetite layer predating the Manchego intrusion.

The contact between country rock and the intrusion was not intersected; however, different types of metasedimentary and granitoid xenoliths reflect strong interaction of the magma with crustal lithologies, possibly in a dynamic magmatic plumbing system. Moreover, mineralised gabbro-norites from Manchego have  $\delta^{34}\text{S}$  values ranging from -11.8 to -8.4 ‰, which clearly demonstrates the addition of crustal sulfur. In fact, these results show that the assimilation of external sulfur is a viable process in the Musgrave Province which may lead to local sulfur saturation of largely S-undersaturated magma.

A review of available geochemical data from the Musgrave Province resulted in a basic classification of prospective gabbro-noritic lithologies in the region. Three geochemically distinct groups can be distinguished on the basis of Cr/V and Ti/Y ratios:

- (1) low Ti series: Cr/V = 1 - 10; Ti/Y = < 320 (mineralised Nebo-Babel-like affinity; Ni-rich)
- (2) intermediate Ti series: Cr/V = 0.1 - 0.4; Ti/Y = 280 - 620 (mineralised Manchego-like affinity; Cu-rich)
- (3) high Ti series: Cr/V = 0.4 - 1.1; Ti/Y = > 600 (No known occurrence of sulfide mineralisation so far)

The classification may be used as a first-order exploration tool to identify prospective rock types in the region. The Manchego Prospect provides compelling evidence for the availability of external sulfur which can be assimilated virtually anywhere in the Musgrave Province. Hence, Manchego shows that the region represents a highly prospective environment for the formation of sulfide deposits.

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## Key characteristics of contact-style PGE-Cu-Ni mineralisation in the Early Proterozoic Monchegorsk Complex, Kola Peninsula, Russia

by

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The 2.5 Ga mafic-ultramafic Monchegorsk Complex (MC) is located in the centre of the Kola Peninsula in Russia. It comprises at least two distinct intrusions covering an area of ~550 km<sup>2</sup>: the predominantly ultramafic Monchepluton (~65 km<sup>2</sup>) and the mafic Main Ridge Massif (~485 km<sup>2</sup>) making it one of the largest layered intrusions on Earth. The MC occurs together with a number of other mafic-ultramafic intrusions across the Fennoscandian Shield; however, almost all of them are slightly younger, at 2.44 Ga. The older intrusions occur exclusively in the Russia portion of the Fennoscandian Shield. The reason for this remains under debate.

The Monchepluton intruded Archean high-grade metamorphic basement (metapelites, quartzites, banded iron formation, dioritic gneisses). It is crescent-shaped and consists of six sub-massifs arranged in two branches. The NNE-trending ultramafic branch (approx. 7 km across) is referred to as "NKT Massif" and comprises Mts. Nittis, Kumuzh'ya and Travyanaya. The W-trending mafic-ultramafic branch is slightly longer with 9 km and consists of Mts. Sopcha, Nyud and Poaz. Exploration in the area is currently focused on contact-style PGE-Cu-Ni mineralisation hosted by the ultramafic Mt. Nittis. Drilling by Eurasia Mining in 2013 yielded intersections of up to 10.9 ppm Pt + Pd over 5.9 m.

Petrographically, the igneous body mainly consists of strongly layered medium-grained orthopyroxenite. Sulfide mineralisation is concentrated at the basal contact between footwall gneisses and the orthopyroxenite in the form of interstitial blebs as well as in thin near-vertical veins overlying the basal mineralisation. The sulfide mineralogy consists of pyrrhotite, pentlandite, chalcopyrite and minor pyrite reaching up to 10 vol % of the rock. The mineral chemistry of samples from Mt. Nittis shows a distinct ~ 200 m wide basal compositional reversal with Mg# of orthopyroxene progressively increasing from 83.6 at the bottom to 86.1 at the top. Similarly, the Mg# of clinopyroxene shows an upward increase from 83.7 to 88.9.

This pronounced compositional reversal at the base of Mt. Nittis is characteristic of many other layered intrusions. Whether this feature reflects contamination of the initial magma by footwall gneisses or increased amounts of trapped liquid due to elevated cooling rates within the contact zone has yet to be determined. However, this type of mineralisation tends to be rather consistent along strike; hence, the NKT Massif has significant potential for hosting further contact-style PGE-Ni-Cu mineralisation as it is likely that the basal contact can be traced for the entire length of the NKT Massif.

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# **The Avebury Nickel deposit, Tasmania, Australia: Key features of a significant hydrothermal nickel sulfide deposit**

by

**Reid R. Keays\***

The Avebury Ni deposit, which has a Ni resource of  $22 \times 10^6$  tonnes @ 0.97 % Ni, occurs along the contact of a Cambrian (~510 Ma) ultramafic sill thrust onto volcanogenic sediments of the neo-Proterozoic Crimson Creek Formation. The entire sequence was overturned following thrusting. The Avebury ultramafic lies within the contact aureole of the 361 Ma Heemskirk Granite the intrusion of which resulted in highly elevated Bi, As, Sb, Mo and W in both mineralized and sulfide-poor ultramafic host rocks as well as the development of skarns in both the ultramafics and the volcanogenic sediments adjacent to them. The mineralization, which is dominated by pentlandite with lesser amounts of pyrrhotite, occurs both in the serpentinized ultramafics and the skarns.

The mineralized samples have very low PGE contents. Samples analysed in this study with > 1% Ni average (in ppm) 47,800 Ni and 178 Cu, and (in ppb) 3.1 Ir, 6.3 Ru, 0.7 Rh, 1.9 Pt, 8.2 Pd and 83 Au. Iridium, Ru and Rh are strongly correlated with each other and their concentrations in both the unmineralized and mineralized ultramafics are typical of those of sulfide-poor high MgO cumulates elsewhere. The absence of any form of correlation between Ru, Ir and Pt with Ni, as well as the low PGE contents of the Avebury Ni sulfides, rules out the possibility that Avebury is a strongly metasomatized magmatic Ni sulfide deposit. This interpretation is supported by the strong heavy S isotope signature of the mineralization, averaging  $17.3 \pm 1.1$  ‰; this signature is much higher than that of all magmatic Ni sulfide deposits with the exception of Noril'sk and Duluth.

Evidence that the Ni mineralization is hydrothermal in origin is provided by strong correlations between Au and Ni as well as between “granophile” elements such as Bi and Ni. The absence of any significant Ni depletion in the unmineralized ultramafics suggests that these cannot have been the source of the Ni in the Avebury deposit. In addition, sulfide-poor co-magmatic ultramafics elsewhere in Tasmania have very low Cu and Pd contents and hence would be poor source rocks for the mineralization.

The strong correlation between Pd and Ni suggests that both were sourced from magmatic Ni-Cu-PGE sulfides somewhere at depth within the hydrothermal plumbing system of the Avebury Ni deposit. The mineralization was deposited along the permeable thrust contact between the ultramafics and the volcanogenic sediments.

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## **Platinum-group element concentrations in base-metal sulfides from the Platreef, Mogalakwena Mine, Bushveld Complex, South Africa**

by

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Base metal sulfides (BMS) are important host minerals for platinum-group elements (PGE) in orthomagmatic Ni-Cu-PGE deposits. Therefore, a detailed mineralogical and an in situ laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) analysis of trace elements was conducted on the BMS of mineralised samples of the Overysel and Sandsloot localities in the Mogalakwena Mine of the Platreef from the northern Bushveld Complex. Observed PGE enrichment trends in the BMS are similar in the Overysel and Sandsloot samples, however, the overall PGE concentrations in the Overysel BMS are lower than those in the Sandsloot BMS. Nevertheless, a general decoupling of the PGE from the BMS due to fluid activity as discussed for the Sandsloot reef lithologies and a respective enrichment of the footwall lithologies was not observed. A major portion of the PGE mineralisation at Overysel and Sandsloot is associated with the presence of BMS as is indicated by a positive PGE-S correlation, whereas an excellent PGE-Ni correlation (especially at Overysel) indicates that pentlandite is the major PGE-carrier. These results are corroborated by the trace element contents of the BMS and a mass balance calculation. For instance, the detailed LA-ICP-MS BMS study of Overysel and Sandsloot samples revealed average concentrations of 65-165 ppm Pd and 0.17-12.7 Rh ppm at Overysel and 156 – 412 ppm Pd and 18 - 57 ppm Rh at Sandsloot in the pentlandite of both the footwall and reef pyroxenites. However, chalcopyrite and pyrrhotite are almost devoid of PGE. Platinum and the IPGE (Ir, Os, Ru) are very low in the BMS and therefore, must be hosted in discrete PGM grains, which is supported by the mass balance calculations and the actual presence of PGM grains in both sample suites, thereby explaining the calculated gap between the whole-rock PPGE concentrations and the PPGE concentration in the mineral phases as revealed by the mass balance calculation.

The PGE concentrations in the BMS and the complementary mass balance calculations are in general agreement with those of the Merensky Reef and the UG-2, in both of which large proportions of the whole-rock Pd and Rh are hosted by pentlandite, while Pt and the IPGE mainly occur in PGM rather than hosted by BMS. However, when comparing our results to those of the Merensky Reef and the UG2 the average Pd and Rh concentrations in pentlandite are distinctly lower in the Platreef.

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# **Melanocratic norite bodies of the Sudbury Igneous Complex, Canada: remnants of a tectonically-disrupted roof rock sequence?**

by

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The Sudbury Igneous Complex (SIC) has formed from a melt sheet generated in a matter of minutes by a large asteroid impact. Subsequent closed-system cooling and crystallization of the melt sheet is thought to have produced a sequence of norite, quartz gabbro, and granophyre from base to top. The recent discovery of several abrupt compositional reversals within norite and quartz gabbro sequences about one to two km above the base of the complex suggests, however, that this simple story of intrachamber evolution of the SIC must be questioned. The compositional reversals are associated with ~10 to 350 m thick sulfide-bearing melanocratic norite bodies (MNB) which are similar to the Sublayer mafic norites at the base of the SIC in major element composition and in occurrence of disseminated sulfides. The Sublayer norites are, however, different from them in that the MNB have both orthopyroxene and plagioclase as cumulus phases, contain a lesser amount of interstitial material, and show a well-developed plagioclase lamination. The MNB are characterized by elevated orthopyroxene content, whole-rock MgO abundance and An-content of plagioclase. Notably, the MNB are indistinguishable from host norite and quartz gabbro in incompatible element concentration ratios (e.g. La/Y) and in whole-rock Nd isotopic composition. In particular, the initial  $\epsilon_{\text{Nd}}$  in the MNB (-8.0) are within error of those in all mafic rocks of the SIC. A geochemical affinity of all noritic rocks of the SIC is also illustrated by similar primitive mantle-normalized trace element concentration patterns that show prominent Nb, Ta, P and Ti negative anomalies. Three explanations for the origin of the MNB can be envisaged in the context of a closed-system model for the SIC: (1) a fault-induced structural repetition of weakly mineralized Sublayer norites; (2) a reversal in crystallization sequence in response to a sudden change in lithostatic/fluid pressure in the magma chamber; (3) a lateral displacement of resident magma from neighboring sub-chambers of the SIC. None of these explanations appears to be adequate to explain certain features of the MNB. As an alternative, we propose here that these bodies are autholiths of the initially existed rock sequence that crystallized from roof downwards but was later disrupted by tectonics and collapsed on the chamber floor. If proven true, this novel idea will require a substantial re-evaluation of current models for internal crystallization and differentiation of impact melt and possibly for origin of Cu-Ni-PGE sulfide ores of the SIC.

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# Experimental and Theoretical Studies of Metal Speciation in Ore-Forming Vapors

by

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The molecular-scale speciation and stability of metal complexes and clusters in low-density water vapor is an emerging new field in geochemistry, with important implications for our understanding of the transport and deposition of metals in the Earth's crust. Ion resonance mass spectrometry and IR spectroscopy in combination with molecular simulation techniques, can provide new insight into the composition, structure and energetic properties of metal species, and as such, deliver important information with regard to the distribution of molecular metal clusters in hydrothermal ore fluids, in particular, in systems dominated by fluids with gas-like characteristics. This presentation will focus on a set of preliminary experimental and theoretical studies of the Pd-, Pt- and Cu-halide systems, and in particular, the role that volatiles (e.g., H<sub>2</sub>O, H<sub>2</sub>S and NH<sub>3</sub>) have on the stability of polynuclear Pd-, Pt-, Cu (and Au) clusters. For example, electrospray mass spectrometric experiments of aqueous CuCl<sub>2</sub> solutions demonstrate rapid and extensive copper-chloride complexation and aggregation toward large polynuclear [Cu(CuCl<sub>2</sub>)<sub>n</sub>]<sup>+2</sup> species and corresponding solvated forms [Cu(H<sub>2</sub>O)<sub>n</sub>]<sup>m+</sup> and [Cu(CuCl<sub>2</sub>)<sub>m</sub>(H<sub>2</sub>O)<sub>n</sub>]<sup>m+</sup>. Results from theoretical quantum chemical studies of [Cu(H<sub>2</sub>O)<sub>n</sub>]<sup>m+</sup> and [Cu(CuCl<sub>2</sub>)<sub>m</sub>(H<sub>2</sub>O)<sub>n</sub>]<sup>m+</sup> and more complex molecular clusters show that at hydrothermal conditions, low-density aqueous fluids contain appreciable levels of ionised copper species. These findings align well with previous experimental studies demonstrating that the solubility of ions (both metals and non-metals) in water vapor is premised on the formation of highly stable molecular ions, especially in fluids with low dielectric constant values [Fernandez-Prini et al. 2004]. Indeed, clusters containing solvated protons and more complexes molecular ions bound to geochemically important molecules such as H<sub>2</sub>O, H<sub>2</sub>S and NH<sub>3</sub> [Lemke and Seward 2008] have been observed in boiling water (steam pH). The priority of our research group is therefore to obtain reliable spectroscopic and thermodynamic data on metal clustering and solvation equilibria pertinent to transport and aggregation processes at hydrothermal conditions. The lack of such important data is currently a major obstacle in our understanding of the formation of ore deposits from metal-charged aqueous vapors.

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# **The roles of xenoliths, xenocrysts, xenomelts, xenovolatiles, and skarns in the genesis of sulfide-rich magmatic Ni-Cu-(PGE) deposits and chromite-rich magmatic Cr deposits**

by

**CM Leshner<sup>1</sup>**

It is now generally accepted, for a wide range of geological, geochemical, isotopic, thermodynamic, and fluid dynamic reasons, that the sulfide in high-S magmatic Ni-Cu-(PGE) deposits (e.g., Kambalda, Noril'sk, Pechenga, Raglan, Sudbury, Thompson, Voisey's Bay) is derived by melting of country rocks during lava/magma emplacement and that because the solubility of sulfide in silicate melts is so low, that it must have existed as an initially Co-Ni-Cu-PGE-poor sulfide xenomelt that was upgraded through interaction with the magma during transport and emplacement. Similar arguments can be made that the oxide in chromite-rich deposits (e.g., Black Thor-Blackbird, Inyala, Ipeuira-Medrado, Kemi, Nkomati, Sukinda) may have been derived by partial melting of country rocks during lava/magma emplacement and not because the solubility of oxide in most silicate melts is so low, that it have existed as initially Cr-poor Fe ± Ti oxide xenocrysts that were upgraded through interaction with the magma during transport and emplacement. Metal tenors of both sulfides and chromite will vary with magma:sulfide mass ratio (R factor). Silicate xenomelts appear to be only rarely preserved, but are depleted in chalcophile or ferrous metals relative to the protoliths (e.g., Kambalda). Xenoliths may be 1) *passively* associated with Ni-Cu-(PGE) mineralization, where the association reflects hydrodynamic equivalence during transport (e.g., Sudbury offset dikes) or 2) *actively* associated with Ni-Cu-(PGE) mineralization, where they represent residues of *S-rich* country rocks that provided the S in the deposits (e.g., Duluth, Voisey's Bay) or where they are residues of *S-poor* country rocks that contaminated the invading magma, lowered sulfide solubility, and locally generated small amounts of Ni-Cu-(PGE) sulfides (e.g., Black Label Hybrid Zone). Iron-rich skarns developed along the margins of sulfide veins and felsic country rocks played an active role in fractionating sulfide melts to extreme Cu-Ni-rich compositions (e.g., Sudbury bornite-millerite ores). Xenovolatiles have normally been considered to have played only a passive role, but it is now appreciated that the vesicular (now amygdaloidal) caps on many Ni-Cu-(PGE) blebs (e.g., Alexo, Kambalda, Noril'sk, Raglan) may have retarded settling – or in some cases (e.g., Dundonald, Fred's Flow) even floated – coarse dense sulfides. Xenoliths, xenocrysts, xenomelts, and xenovolatiles are more likely to be preserved in cooler basaltic magmas than in hotter komatiitic magmas, and are more likely to be preserved in less dynamic (less turbulent) systems/domain/phases than in more dynamic (more turbulent) systems/domains/phases. Critically, if skarns/residues, xenoliths, xenocrysts, xenomelts, and/or xenovolatiles are present, they must be included in elemental and isotopic R-factor mass balance calculations.

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## **Diverse geodynamic settings for major magmatic sulfide deposits in China: with exploration implications**

by

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Magmatic Fe-Ni-Cu sulfide deposits in China are located in three principal geodynamic settings: (1) continental areas associated with mantle plume, (2) rift zones in the continental margins, and (3) convergent tectonic zones. The first type is associated with voluminous flood basalts, such as those in the mafic-ultramafic intrusions of the Emeishan Large Igneous Province in SW China. The second type is represented by the Jinchuan deposit that occurs in the SW margin of the North China Craton. The third type can be further divided into those that formed during active subduction and those that formed post-subduction, such as the newly-discovered Xiarihamu and Poyi deposits in western China, respectively. All of the major Fe-Ni-Cu sulfide deposits in China appear to have formed from PGE-depleted magma, produced either from low-degree melting of the mantle leaving PGE-rich sulfide liquid behind or from a previous sulfide saturation event in the conduit systems. All of the major magmatic sulfide deposits in China show Os isotopic evidence for extensive crustal contamination. The addition of external sulfur appears to be essential for the generation of ore quality deposits. The discovery of the Xiarihamu deposit reveals that convergent tectonic zones also have potential for major Fe-Ni-Cu sulfide deposits. The Emeishan Large Igneous Province shows many similarities with the Siberian flood basalt province and exploration there for larger magmatic Fe-Ni-Cu sulfide deposits associated with sub-volcanic intrusions should continue.

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# Genesis of the Jinbaoshan PGE-(Cu)-(Ni) deposit, Western Yunnan, China: constraints from geochemistry of PGEs and mineralogy of base metal sulfides and PGMs

by

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The ~260 Ma Jinbaoshan PGE-(Cu)-(Ni) deposit is located in the western part of the Yangtze Plate, along the eastern margin of the Red River fault system in southwest China, and is the largest PGE-(Cu)-(Ni) deposit in China. The Jinbaoshan intrusion is exposed as a large sill-like ultramafic intrusion approximately 5 km long, up to 1.2 km wide, and up to 170 m thick. It is composed mainly of wehrlite (92 vol.%) with minor gabbro and clinopyroxenite. The mineralization occurs as a stratiform or lensoid bodies in the central part of the wehrlite at multiple levels of the intrusion. The sulfide assemblage includes pyrite, chalcopyrite, millerite, violarite, and magnetite. The sulfide assemblage is much richer in S and much poorer in Fe than most primary magmatic sulfide assemblages, most likely representing oxidation of an original pyrrhotitepentlandite-chalcopyrite  $\pm$  magnetite assemblage. Platinum-group minerals (PGMs) are 0.5-10  $\mu\text{m}$  in diameter and include moncheite  $\text{Pt}(\text{Te},\text{Bi})_2$ , merteite I  $\text{Pd}_{11}(\text{Sb},\text{As})_4$ , atokite or rustenburgite  $(\text{Pd},\text{Pt})_3\text{Sn}$ , irarsite  $\text{IrAsS}$ , and sperrylite  $\text{PtAs}_2$ , hosted mainly by silicates, magnetite, violarite and millerite. Nearly all merteite I grains occur at the edges of their host minerals (violarite and millerite), appearing to be anhedral in metagabbroic rock. Most samples exhibit strong positive correlations of Pt-Pd-Ru-Rh vs Ir and Pd vs Pt, consistent with a primary magmatic origin. Mineralized rocks have a significantly lower Nb/Th, higher h/Yb, lower  $\epsilon\text{Nd}$ , and higher  $\epsilon\text{Sr}$  than typical mantle melts, suggesting that the magma experienced up to ~20% contamination by average Yangtze upper crust, which may have induced segregation of a Ni-Cu-PGE enriched sulfide melt. Primitive mantle-normalized PGE patterns have strong negative Ru and slight negative Rh anomalies, both of which are known to also partition into chromite, indicating crystallization of chromite at an early stage. The mineralization is enriched in  $\text{PGE} > \text{Cu} > \text{Ni}$ , consistent with formation at a high magma:sulfide ratio ( $R \sim 10000$ ), suggesting a dynamic open magmatic system in which the segregated sulfide liquid interacted with a very large mass of magma. The Jinbaoshan deposit is of magmatic origin but also has experienced secondary alteration processes. At a later stage the ores were hydrothermal altered by S-rich fluids, which modified the primary sulfide assemblage, textures of PGMs and also had a limited influence on PGE distributions.

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# Petrogenesis and Ni-Cu sulfide potential of mafic-ultramafic rocks in the Fraser Zone within the Albany–Fraser Orogen, Western Australia

by

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The Albany Fraser orogen formed during reworking of the Yilgarn Craton, along with variable additions of juvenile mantle material, from at least 1810 Ma to 1140 Ma. The Fraser Zone is a 425 km long and 50 km wide geophysically distinct belt near the northwestern edge of the orogen, hosting abundant sills of predominantly metagabbroic non-cumulate rocks, but including larger cumulate bodies, all emplaced at c. 1300 Ma. The gabbroic rocks are interpreted to have crystallized from a basaltic magma that had ~8.8% MgO, 185 ppm Ni, 51 ppm Cu, and extremely low contents of platinum-group elements (PGE, <1 ppb). Levels of high field-strength elements (HFSE) in the least enriched rocks indicate that the magma was derived from a mantle source more depleted than a MORB source. Isotope and trace element systematics suggest that the magma was contaminated ( $\epsilon\text{Nd}$  0 to -2 throughout, La/Nb around 3) with small (<10%) amounts of crust before and during ascent and emplacement. Larger bodies of cumulate rocks show evidence for additional contamination, at the emplacement level, with country-rock metasedimentary rocks or their anatectic melts. The area has been the focus of exploration for Ni-Cu sulfides following the discovery of the Nova deposit in 2012 in an intrusion consisting of olivine gabbro-noritic, noritic and peridotitic cumulates, interlayered with metasedimentary rocks belonging to the Snowys Dam Formation of the Arid Basin. Disseminated sulfides from a drillcore intersecting the structurally upper portion of the intrusion, above the main ore zone, have tenors of ~3-6.3 % Ni, 1.8-6 % Cu and mostly <500 ppb PGE, suggesting derivation from magma with the same composition as the regional Fraser Zone metagabbroic sills, at R factors of ~1500. However, the Nova rocks tend to have higher  $\epsilon\text{Sr}$  (38-52) and more variable  $\delta^{34}\text{S}$  (-2 to +4) than the regional metagabbros ( $\epsilon\text{Sr}$  17-32,  $\delta^{34}\text{S}$  around 0), consistent with the geochemical evidence for enhanced crustal assimilation of the metasedimentary country-rock in a relatively large magma staging chamber from which pulses of sulfide bearing, crystal-charged magmas were emplaced at slightly different crustal levels. Preliminary investigations suggest that the critical factors determining whether or not Fraser Zone mafic magmas are mineralized relate to local geodynamic conditions that allow large magma chambers to endure long enough to sequester country-rock sulfur. Here we present new data from regional exploration targets showing that rocks with the petrological and geochemical characteristics of the Nova deposit occur elsewhere within the Fraser Zone.

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# Fennoscandian magmatic Ni-(Cu-PGE) deposits – composition of ore and parental magma through time

by

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The most important magmatic Ni-(Cu-PGE) deposits within the Fennoscandian Shield are found in the central and eastern part of the Shield, which is defined by three large-scale crustal units: the Archaean basement ( $\geq 2.5$  Ga), the Palaeoproterozoic (2.5–1.9 Ga) supracrustal cover, and the Svecofennian orogenic belt (1.9–1.8 Ga).

Only a few komatiite-hosted Ni-(Cu-PGE) deposits have been discovered in the Archaean greenstone belts. They are found mostly in the greenstone belts (ca. 2.8 Ga) in eastern part of Finland, in the Karelian greenstone belts in Russia and in the Rommaeno complex in Finnish Lapland. Many of the 2.44–2.50 Ga Palaeoproterozoic layered intrusions in Finland and Russia are PGE-Ni-Cu-mineralized and host the most significant PGE deposits in Europe. The mafic-ultramafic magmatism at ca. 2.05 Ga produced several significant Ni-Cu-PGE deposits in the central Lapland greenstone belt, like Kevitsa and Sakatti. The 1.97 Ga ferropicritic sills ( $\pm$ extrusives) host the world class Pechenga Ni-Cu deposit in Kola Peninsula, Russia. During the last century the Svecofennian (1.88 Ga) orogenic Ni-Cu deposits were the most important source of nickel in Finland's mining history. In Sweden Svecofennian deposits have been explored but only limited mining has taken place. Numerous orogenic Meso-Proterozoic and Caledonian Ni-Cu-mineralized intrusions occur in Norway, which was the world's leading nickel producer in the early 1870s.

The MgO content of the parental magma for several Fennoscandian magmatic sulfide deposits was estimated and compared to the composition of the related Ni-(Cu-PGE) ores, especially to the Ni/Cu ratio and also to the PGE content. The estimated MgO content of the parental magma in the selected deposits varies from around 7 w % to 16 w % in basaltic to komatiitic basalt and picritic systems and up to 24 w % in more magnesian komatiitic systems while Ni/Cu ratio varies between 0.7 – 15. The metal contents of the sulfide fraction as a whole correlate with the MgO contents of the parental magma: the more magnesian the magma the higher the Ni/Cu ratio of the ore. The PGE content is highest within komatiitic basalt hosted deposits. The differences between the modelled (R-factor, multistage dissolution-upgrading model) and observed Ni/Cu ratios may result e.g. from copper loss during post-magmatic processes (serpentinisation and/or metamorphism) or from the fact that part of the sulfide ore is still unknown. The latter alternative can be used to guide further exploration.

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# Genesis and exploration potential of the high Ni tenor magmatic sulfide deposits in the Eastern Tianshan, northwest China: constraints from PGE geochemistry and Os–S isotopes of the Huangshannan deposit

by

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The Huangshannan magmatic sulfide Ni-Cu deposit is one of the Permian magmatic Ni-Cu deposits located in the Eastern Tianshan, northwest China, southern Central Asian Orogenic belt. It is characterized by high lherzolite and olivine websterite (15-20 wt.%) with high Ni tenor sulfides, much higher than other deposits regionally, as well as in China. Sulfides of the Huangshannan deposit are composed of pentlandite, chalcopyrite and pyrrhotite, and the host rock is relatively fresh, indicating that the high Ni tenors are the result of primary magmatic processes rather than alteration. High Ni tenors can result from either sulfide-olivine-silicate equilibrium (such as picrite or high Mg basalt), or sulfide segregation from extremely Ni rich magma (such as magma derived from pyroxenite-rich mantle source). Modelling results show that the high Ni tenors of the sulfides could be generated by simple sulfide-olivine equilibrium at QFM 1, for a magma with 450 ppm Ni, and R factor values (magma/sulfide ratio) between 100 and 1500.

In addition, PGE concentrations are well correlated, also suggesting that the sulfide composition is mainly controlled by R factor values. The R factor is between 100 and 1500 if the parental magma have 0.1 ppb Os, 0.1 ppb Ir and 0.05 ppb Pd. However, Pt and Pd anomalies are observed in fresh, sulfide rich samples (S>4 wt.%). Because sulfide-rich samples are also depleted in Cu, and interstitial sulfides in those samples are connected, the Pt and Pd anomalies are attributed to monosulfide solid solution (MSS) fractionation and Cu-rich sulfide liquid percolation during MSS fraction. This finding indicates that Pt anomaly in sulfide-rich rocks from magmatic Ni-Cu deposits regionally might be the primary magmatic feature rather than formed by hydrothermal process.

The  $\delta^{34}\text{S}$  values of sulfides in lherzolite range from -0.4 to 0.8‰, values which are similar to typical mantle values, and thus an evaluation of crustal sulfur addition based on  $\delta^{34}\text{S}$  values alone is difficult.  $^{187}\text{Os}/^{188}\text{Os}_{(280\text{Ma})}$  values of the lherzolite samples vary from 0.27 to 0.37 and the  $\gamma\text{Os}_{(280\text{Ma})}$  values vary from 110 to 189, indicating significant magma interactions with crustal material which is rich in radioactive Os. Relative constrained  $\gamma\text{Os}_{(280\text{Ma})}$  values indicates that crustal material addition might occur at depth before the magma arrived at the Huangshannan chamber as a result of bulk contamination or selective contamination. Simple two-component mixing models suggest that the bulk crustal addition is ~20-30%, which is consistent with the O-Nd-Hf isotope study for the intrusion.

Regionally, high Ni tenor deposits have not been reported except the Huangshannan deposit, however, many intrusions with high Ni content in olivine are present in the NW China, such as the Ehongwa, Luodong, Poyi and Poshi intrusions. In terms of the studies on the Huangshannan high Ni tenor deposits and other high Ni tenor deposits worldwide (Mirabela, and Bethno), those intrusions in NW China are capable of forming high Ni tenor sulfides due to olivine-sulfide-silicate equilibrium, and thus could be candidates for exploring high Ni tenor sulfides.

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# Genesis of the Medek intrusion, Russia: evidence from fluid inclusions, mineralogy and geochemistry of platinum group elements

by

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The Medek intrusion, located at the margin of the Siberian craton, intruded a Neoproterozoic metasedimentary sequence of gneisses, marbles and orthoamphibolites. The Medek intrusion is composed of serpentinised, tectonised dunite and wehrlite, and displays the most intense alteration near the margin of the intrusion at the contact with metasedimentary rocks. Fresh wehrlite occurs only in the central parts of the intrusion. The primary igneous minerals are Cr-spinel followed by olivine, orthopyroxene and clinopyroxene. Orthopyroxene (En<sub>88-72</sub>) is less abundant than clinopyroxene (En<sub>45-62</sub>Wo<sub>37-45</sub>Fs<sub>1-11</sub>). Cr-spinel occurs mainly as accessory mineral phase, occasionally enclosed by olivine (Fo<sub>92-74</sub>). Ilmenite is typically found as lamellae within the Cr-spinel but also as individual crystals both within olivine and Cr-spinel.

Two types of fluid-melt inclusions and multiphase inclusions containing partly molten olivine crystals were identified in Cr-spinel from wehrlite. The composition of glasses in type I inclusions is similar to that of low-Ti and low-K picobasalts. Glasses in type II inclusions have high Ti (up to 3.7 wt.%), Fe (up to 23.5 wt.%), P (up to 2.3 wt.%) and low SiO<sub>2</sub> (32.8 wt.%) contents, which differ drastically from compositions of the most common rock types and previously analyzed inclusions in Cr-spinel hosts. The analysis of phase composition of heated and quenched melt inclusions shows that the parental magmas of the Medek intrusion rocks were more magnesian than picobasaltic melts.

The Medek ultramafic intrusion contains Ni and PGE mineralisation in the form of disseminated ores. The most abundant sulfide assemblage is interstitial between cumulus olivine and clinopyroxene. The base-metal mineral assemblage is, in order of decreasing abundance, pentlandite, pyrrhotite and chalcopyrite. Original sulfides are mainly replaced by heazlewoodite, chalcocite and mackinawite. The interstitial sulfide assemblage displays a primary magmatic position between olivine grains. Sulfides are penetrated by platy intergrowths of chlorite and serpentine. The disseminated sulfide ores are characterised by variable but generally high PGE concentrations: 3900-25000 ppb Pt, 7000-139000 ppb Pd, 80-2000 ppb Ir, 140-1800 ppb Ru, and 90-800 ppb Rh in 100 % sulfides.

Representative drill core samples through the Medek intrusion were used to establish variations in whole-rock geochemistry and mineralogy. These variations demonstrate reverse zoning within the intrusion from top to bottom, which are consistent with magmatic differentiation in a sill-like body, which was serpentinised and then overturned.

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## **A new komatiite-hosted Ni-Cu-PGE event in the Eastern Goldfields Superterrane**

by

**David R. Mole<sup>1</sup>, Lauren Burley<sup>2</sup>, Stephen J. Barnes<sup>1</sup>**

The Fisher East belt forms the eastern-most portion of the Dingo Range greenstone belt, located in the north Eastern Goldfields Superterrane, on the Kurnalpi/Burtville Terrane margin, approximately 450 km north of Kalgoorlie. The nickel potential of this region was identified on its position along strike with the 2.8 Ga Windara nickel deposit. The discovery of a number of small komatiite-hosted nickel occurrences in the area, including AK47, Collurabbie and Rosie, demonstrate the potential of the region.

This potential was realised in 2013 when Rox Resources intersected nickel sulfide mineralisation at the Camelwood prospect. Further exploration led to the delineation of four additional prospects at Cannonball, Musket and Sabre. These deposits represent the largest komatiite-hosted Ni-Cu-PGE 'camp' in the north Eastern Goldfields.

In order to understand the context of the komatiites and nickel mineralisation within the geological and architectural evolution of the Yilgarn Craton, a selection of samples were taken through the drilled stratigraphy that represents the basal portion of the Fisher East Belt. This stratigraphy consists of an overturned sequence of felsic volcanic/volcaniclastic/epiclastic rocks (with minor shales) in the footwall, followed by differentiated komatiite flows, with basal Ni-Cu-PGE mineralisation in 'channelized' regions. The hanging Wall stratigraphy is complex but appears to consist of quartzite, basalt and mafic-intermediate volcaniclastics.

New sensitive high-resolution mass spectrometry (SHRIMP) U-Pb geochronology from felsic volcaniclastics and volcanics from footwall rocks yield ages from 2955 to 2940 Ma, and a single age from a hanging-wall intermediate volcaniclastic yields ca. 2840 Ma. This indicates that the komatiites are between 2940 and 2840 Myrs old. This is significantly older than both the world-class 2.7 Ga deposits of the Kalgoorlie Terrane, and also the 2.8 Ga Windarra deposit, and makes the Fisher East komatiites and their host Ni-Cu-PGE sulfides the oldest currently known in the Eastern Goldfields.

However, while there may not be a correlative system east of the Ida fault, new geochronology from the Forrestania belt (Younami Terrane), which hosts the Flying Fox and Spotted Quoll komatiite-hosted Ni-Cu-PGE systems, yield a footwall age of ca. 2920-2950 Ma. This suggests that both the Fisher East and Forrestania mineralised komatiite systems may have been formed by the same mantle plume event, with their locations controlled by pre-existing lithospheric architecture. It also indicates that the Fisher East belt is more akin to the Burtville Terrane stratigraphy, and may have been part of the Younami Terrane prior to ca. 2750 Ma.

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# Phosphorite and metal associations in the Cambrian metalliferous black shales of the Niutitang Formation

by

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David Paterson,<sup>3</sup> Haifeng Fan<sup>4</sup> and Hanjie We

During the Early Cambrian, a transition from oxygen-deficient to oxygenated oceans triggered the evolution of metazoan radiation and the genesis of sub-economic Ni, Mo, Rare Earth Elements (REE) and Platinum Group Element (PGE) deposits in shallow water environments on the Yangtze platform in China. A thin accumulation (5 – 20 cm) of Ni, Mo, Au, Ag, Se, Cr, V, Zn, U and PGEs and other metals including REE is developed within the Lower Cambrian Niutitang Formation, and can be traced along the same stratigraphic horizon over distances up to 2000 kilometers. The genesis of this strata-bound deposit remains poorly understood and highly controversial. Therefore, this is one of the most enigmatic examples of a sediment-hosted base and precious metal deposit showing an association of ore-grade metals with organic matter.

The Niutitang Formation is composed of nodular and bedded phosphorites, and a Ni-Mo enriched and sulfide-bearing horizon within organic carbon-rich black shales. The present study aims to investigate in detail the spatial distribution of Ni, Mo, Cu, Se, V, Zn, U and PGEs in this unusual ore layer, providing further insights into the genesis of this metal accumulation. A multi-proxy approach was used with total organic carbon, XRD and whole rock geochemical analyses to investigate bulk compositions. To get further insight into the spatial distributions and metal species association, microbeam XRF mapping, SEM, Synchrotron XRF mapping and EPMA were applied on samples from the mineralized horizon. LA-ICPMS analyses were also performed to investigate PGE associations. Analyses of the mineralized horizon revealed the presence of fine-scale segregations of metals. Brecciated textures of black shales with disrupted organic matter lenses and fragmented phosphorites were observed. Phosphorite nodules are surrounded by high concentrations of specific elements (e.g., As) accumulating on the edge of the nodules whereas V, Zn and Cu appear to be associated with the organic-rich matrix. Nickel is mainly present as Ni-sulfide (millerite, vaesite, polydymite and gersdorffite) and the PGEs (Pt, Pd, Rh) show a high affinity with them, although Pd also appears to be strongly associated with phosphorite nodules. The strong variations in metal distributions suggest rapid shifts in redox conditions. Mercury was also imaged for the first time in these Cambrian metalliferous shales. This fine-scale study of metals, organic-rich matrix and phosphorite nodules provides a better understanding of metal association and distribution in this unusual, highly anoxic and sulfidic sedimentary system.

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## Investigations of metal associations in the metalliferous black shales of South China and the Nick prospect by X-Ray fluorescence microscopy (XFM)

by

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Shale-hosted Ni-Cu-PGE sulfide occurrences can be associated with large amounts of Mo, Zn, Mn, V and U and represent economic resources. In recent years, metalliferous black shales have proven to represent a valuable resource for Ni (Talvivaara mine in Finland) and other base metals (Red Dog and Howards Pass Pb-Zn deposits, USA and Canada).

In South China, during the Early Cambrian, a thin accumulation of phosphorite containing Ni, Mo, Au, Ag, Se, Cr, V, Zn, U and PGEs occurred in shallow water environments, on the Yangtze platform. This narrow mineralized layer located within 10m of the Proterozoic-Cambrian boundary, crops out for up to 2000 kilometers. This thin ore horizon is particularly enriched in organic matter (OM) (> 10 % TOC), in Mo-Ni-Re-Os-Se-As-Hg-Sb (> 1000\*continental crust) and Ag-Au-Pt-Pd (> 100\*continental crust). This is one of the most enigmatic examples of a sediment-hosted base and precious metal deposit showing an association of ore-grade metals with OM.

Of all known deposits, the Ni-Mo sulfide beds of the Devonian Nick prospect in the Selwyn Basin, Canadian Yukon, display the strongest similarities with the South China black shales. The bed thickness varies between 5 and 15 cm, it is associated with a significant unconformity at the edge of the basin and contains abundant Ni (7.8 % Ni), Mo (0.4 %) and PGE (up to 1050 ppb). The Nick prospect shows a less complex mineralogy than the Niutitang shales, but they both display clastic textures and abundant vaesite. Although a SEDEX mineralization model has been suggested for the Nick deposit, very few studies have focused on the detailed associations and origin of the metals.

XFM combined with the Maia detector (384 detector array) was performed on the Australian Synchrotron XFM beamline to investigate the fine-scale distribution of metals in these rare mineralized horizons. The high-definition images obtained with the Maia detector allow the detection of metal segregation on a wide range of spatial scales. For the first time, detailed mineral structures were investigated in the South China shales and the Nick prospect to gain further understanding of metal deposition in these complex organic-rich sedimentary systems, based on a comparison of two distinct localities. While there is a close grain-scale association between Ni and phosphorite nodules in the Niutitang shales, the same is not seen in Nick, implying that, even though phosphorite may play a role in specific metal accumulation, it is not the primary control on metal deposition.

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# **New insights into the geodynamic setting of komatiite-hosted Ni-sulfide deposits in the Agnew-Wiluna Belt of Western Australia**

by

**Caroline S. Perring\***

The Agnew-Wiluna Belt is perhaps the best endowed terrain in the world with regard to komatiite-hosted Fe-Ni-Cu sulfide mineralization. It hosts two of the largest such deposits, the Type 1 (basal sulfide-rich accumulation) Perseverance deposit with in excess of 1Mt of contained Ni and the Type 2 (internal, disseminated) Mt Keith deposit with in excess of 2.5Mt contained Ni, in addition to several smaller but nonetheless significant deposits each containing in excess of 150kt Ni.

The Agnew-Wiluna Belt is dominated by ultramafic, mafic and felsic volcanic and volcanoclastic rocks dated to between 2720Ma and 2690Ma and extruded subaqueously into an intracratonic rift zone. The Agnew-Wiluna Belt can be divided up into a series of NNW-trending tectonostratigraphic domains: this strong structural grain is likely to be controlled by a zone of deep crustal weakness inherited from an earlier episode of rifting at ~2.81Ga. The greenstones have been subjected to an extensive period of orogenesis, extending from 2690Ma until at least 2650Ma, resulting in peak regional metamorphic grades ranging from greenschist facies at Mt Keith to amphibolite facies at Perseverance and producing a belt-wide sequence of eight deformation events.

A regional-scale program of 3D modelling has allowed the unravelling of this complex tectonic overprint and has shed light on the geodynamic setting of the komatiite-hosted Fe-Ni-Cu sulfide deposits. The dominant primary volcanic grain of the belt (indicated by the unfolded orientation of lava pathways) trended approximately NNE-SSW. Comparison with modern examples of intracratonic rifting indicates that this trend was probably controlled by extension-orthogonal normal faults and suggests that extension within the Agnew-Wiluna Belt at ~2.7Ga was probably oblique to the overall north-northwesterly trend of the rift. Possible transfer zones, oriented NW-SE, are indicated by a series of breaks in the regional gravity image which correlate with dislocations in the regional geology map (marked by a combination of left-lateral jogs in the strike of the NNW-trending domain-bounding faults, regional-scale fold-closures and northwest-trending faults). On a regional scale, the majority of large Fe-Ni-Cu sulfide deposits occur within a few kilometres of these transfer zones, while at the mine scale, the intersection of NW- and NNE-trending synvolcanic faults appears to control the best development of mineralization at Mt Keith, Yakabindie and possibly Cliffs. An understanding of the synvolcanic structural architecture of the Agnew-Wiluna Belt clearly has implications for future exploration for komatiite-hosted Fe-Ni-Cu sulfide mineralization

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## Ni-Cu-PGE and Fe-sulfide mineralisation in the West Musgrave region of Western Australia; learnings from a five year exploration program

by

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The West Musgraves region of Western Australia is remote, under-explored and hosts the 446Mt Nebo-Babel Ni-Cu deposit in 1068-1067Ma Alcurra mafics belonging to the Warakurna LIP. Until recently, few other sulfide occurrences were known to exist. However, a five year exploration program (2009 to 2013) by Anglo American Exploration (Australia) identified 4 styles of sulfide mineralisation across approximately 10,000km<sup>2</sup> of the West Musgraves. Of these only the magmatic Nebo-Babel mineralisation has previously been described.

The 1340–1270Ma Wirku Metamorphics host sulfide mineralisation in amphibolite to granulite facies felsic and mafic rocks at Block 5, Berganost and Periscope. Pyrrhotite-pyrite ± sphalerite ± chalcopyrite occur in felsic metapelites whereas pyrrhotite ± pentlandite ± chalcopyrite occur in mafic metapelites. Sulphur concentrations reach 9.1 wt% at Block 5, whereas Zn to 1.8 wt% and Pb to 0.9 wt% occur at Berganost.  $\delta^{34}\text{S}$  values range from -17‰ at Periscope to +6.3‰ at Block 5.

The 1078-1076Ma G1 layered intrusions host two styles of PGE mineralisation: 1) Stella-type PGE mineralisation associated with bornite, chalcopyrite ± pentlandite in or adjacent to <2m wide magnetite reefs in the Jameson Range; and 2) Skaergaard-type PGE mineralisation associated with bornite, chalcopyrite, pyrrhotite ± pentlandite in heavily disseminated magnetite at the Navigator and Latitude Hill prospects. Pt:Pd ratios range from 1 to 3. Sulphur concentrations up to 0.75 wt% and several zones of apatite enrichment exist, reaching at least 59 m with 1.0 wt % P<sub>2</sub>O<sub>5</sub>.  $\delta^{34}\text{S}$  values average 2.3‰, ranging from -4.9‰ at Navigator to +6.3‰ at Latitude Hill.

A gabbro-norite intrusion geochemically indistinct from the 1068-1067Ma Alcurra Dolerite hosts massive to disseminated magmatic sulfide mineralisation comprising pyrrhotite, chalcopyrite and pentlandite at Manchego. Assays up to 0.62 wt% Cu, 0.47 wt% Ni and 1ppm PGE outline 2 sub-parallel lenses of mineralisation. Distinct gabbro-noritic lithotypes indicate a dynamic magmatic plumbing system. Crustal contamination is recorded by frequently occurring xenoliths in the gabbro-norites and  $\delta^{34}\text{S}$  values from -11.8‰ to -8.4‰.

Siltstone and shale belonging to the <1057Ma Frank Scott Formation of the Bentley Supergroup contains disseminated pyrite that accounts for up to 1.4 wt% S at the Roquefort prospect. Gold assays between 50 and 900ppb occur in the top 70m of shale, and traces of chalcopyrite and sphalerite account for 0.19 wt% Cu and 0.23 wt% Zn at this prospect.  $\delta^{34}\text{S}$  values range from -0.5‰ to +6.0‰.

None of these occurrences are economically exploitable, but most are potential sources of crustal sulphur for magmatic Ni-Cu mineralisation. The information that they provide is significant to this otherwise poorly explored area that until recently was thought to contain very few sulfide occurrences.

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# Lateritic Nickel Deposits

by

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Lateritic nickel deposits (>1% Ni and >130 million tons of Ni) represent about 60% of global Ni resources. Current nickel production mimics this ratio with about 60% of global production supplied by laterite and 40% from sulfides. The current biggest producers of lateritic nickel are the Philippines (21%), Australia (9%), New Caledonia (8%), Indonesia (7%) and Brazil (4%). Lateritic nickel deposits are the result of weathering of serpentinites or partially serpentinised ultramafic rocks. Lateritic nickel deposits are subdivided into 3 sub-types depending on the dominant Ni-host mineralogy and are by order of volumetric importance; (1) Oxide Deposits or “Yellow Laterite” dominated by Ni substituted goethite with an average Ni grade of 1.0 to 1.6%, (2) Hydrous Ni-Mg Silicate Deposits dominated by Ni-serpentine, -chlorite and- talc labelled under the term “garnierite” with an average Ni grade of 2% to 5% and (3) Clay Silicate Deposits dominated by Ni-rich saponite and smectite with an average Ni grade of 1.0 – 1.5 wt%. The genesis of the nickel lateritic deposits shows that the economic and mineralogical characteristics of these deposits are controlled by a complex multiphase evolution.

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## **S, Os and Cu isotope variations between sheet- and conduit-style Ni-Cu-PGE mineralization in the Midcontinent Rift System, USA**

by

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The 1.1 Ga Midcontinent Rift System (MRS) is host to several different types of Ni-Cu-PGE sulfide deposits. Two types of mineralization, in particular, are most common and are referred to as sheet- and conduit- style. Disseminated sulfides (2-5 vol. %) occur within troctolite to gabbro layers in intrusions such as the Partridge River and South Kawishiwi in the Duluth Complex of Minnesota and the Crystal Lake Intrusion in Ontario. Disseminated, net-textured, and massive sulfide mineralization occurs in near vertical olivine-rich dike-like bodies, including the Eagle intrusion in Michigan and the Tamarack Intrusive Complex in Minnesota. The two distinct types of sulfide-rich deposits are characterized by important differences in S, Os and Cu isotope systematics.

Mineralization that is associated with the sheet-style intrusions is characterized by positive and variable  $\delta^{34}\text{S}$  values ranging between 0 and 30 ‰.  $^{187}\text{Os}/^{188}\text{Os}$  ratios are also elevated with values as high as 4.72 and  $\gamma_{\text{Os}}$  values as high as 1175. The S and Os isotope values are similar to those of Proterozoic country rocks and suggest that magma contamination was essential for ore genesis.  $\delta^{65}\text{Cu}$  values of disseminated sulfides in the Duluth Complex range from -0.85 to 0.45 ‰. In sharp contrast the  $\delta^{34}\text{S}$  values of disseminated, net-textured and massive sulfide mineralization at Eagle and Tamarack fall in the range of 0.3 to 4.6 ‰, and  $^{187}\text{Os}/^{188}\text{Os}$  ratios range from 0.1511 to 1.248 with  $\gamma_{\text{Os}}$  values in a much tighter range from 7 to 53.  $\delta^{65}\text{Cu}$  values of the mineralization at Eagle and Tamarack are higher than those of sulfides in the sheet-style mineralization and range from 0.69 to 1.84 ‰.

The conduit-style deposits show S and Os isotope characteristics that may be attributable to dynamic processes of isotope exchange in magma conduits, with  $\delta^{34}\text{S}$  and  $\gamma_{\text{Os}}$  values more similar to those of uncontaminated mantle. The strongly anomalous S and Os isotope ratios of sulfide minerals in the sheet-style intrusions are more similar to those found in sulfidic and carbonaceous Proterozoic country rocks, and are indicative of far less exchange with uncontaminated mantle-derived magmas. The differences between the Cu isotope compositions of the two types of mineralization are difficult to reconcile by similar mechanisms. Differences in Cu isotope values must be related either to the presence of distinct Cu reservoirs in the mantle of the MRS, or to poorly understood Cu isotope fractionation during separation of immiscible sulfide liquids from source magmas.



# The Nebo-Babel Ni-Cu-PGE sulfide deposit, West Musgrave, Western Australia

by

Zoran Seat<sup>1</sup>, Benjamin A. Grguric<sup>2,3</sup>, Jon M.A. Hronsky<sup>1,3,4</sup> and Gregory J. Miles<sup>1</sup>

The Nebo-Babel Ni-Cu-PGE sulfide deposit, located in the West Musgrave Block, Western Australia, is hosted within concentrically zoned, chonolithic, gabbro-norite intrusions emplaced at 1068Ma. The two intrusions are synchronous with the major magmatic Giles Event in Central Australia, which includes the Giles Complex layered mafic-ultramafic intrusions, and the Bentley Supergroup volcanics. The Nebo-Babel intrusions have been emplaced in an amphibolite-granulite facies felsic orthogneiss, extend for about 5 km in an E-W orientation and have a cross section of ~1km x 0.5km. The Babel and Nebo intrusions are separated by the Jameson fault, with an apparent normal throw, and the present geometry most likely represents structural offset of one continuous intrusion.

The Nebo-Babel intrusions consist of at least three chemically related, but temporarily distinct magma pulses. The initial magma pulse which formed marginal units of the intrusion was the most primitive and shows the highest degrees of contamination by the country rocks including mesoscopic xenoliths. The subsequent magma pulses that were emplaced into the core of the intrusion, are more fractionated, but show a lower degree of country rock contamination. Primary igneous mineralogy and textures are well preserved. All of the lithostratigraphic units can be related by crystal fractionation of parental tholeiitic magma with 8-9 wt% MgO. Mineral  $\delta^{18}\text{O}$  values are consistent with typical mantle values and preclude large-scale crustal contamination of the parental magma with anything other than material with similar values.

Mineralisation is confined to the early magma pulses and includes disseminated gabbro-norite hosted sulfides and massive sulfide breccias and stringers. Sulfide Ni-Cu ratios are on average 1:1 and the Ni tenor of the massive sulfides, which have undergone sulfide liquid fractionation, and the disseminated sulfides are very similar. The average  $\delta^{34}\text{S}$  value of the Nebo-Babel disseminated and massive sulfides is  $0.4 \pm 0.2$  per mill, which is consistent with a mantle S source. Distal sulphur saturation is inferred to have been triggered by assimilation of felsic orthogneiss, primarily by Si addition, and perhaps without any external S addition.

The distribution of disseminated sulfides is thought to be controlled by the dynamic magma-emplacement history and resultant internal architecture of the chonolith rather than gravitational settling of the sulfides. Distribution of the massive sulfides however, appears to have been primarily controlled by heterogeneity in the chonolith geometries and the effect that this may have had on the velocity of the magmas, which have carried suspended sulfide liquid droplets.

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## A non-plume model for the Permian protracted (266-286 Ma) basaltic magmatism in northern Xinjiang, western China

by

Shengchao Xue<sup>1,2</sup>, Chusi Li<sup>3</sup>, Kezhang Qin<sup>1</sup>, Dongmei Tang<sup>1</sup>

It is widely accepted that the protracted (261-287 Ma) Ni-Cu sulfide-rich and sulfide-barren mafic-ultramafic intrusions and mafic dikes in the Beishan-Tianshan region in northern Xinjiang, western China are the products of a Permian mantle plume. We challenge this popular view using existing geochronological data for the mafic-ultramafic intrusions as well as our new geochronological data for the mafic dikes. It is well known that due to plate movement above a mantle plume, the emplacement of mantle plume-derived magma in the crust should change its location with time, e.g., ~1000 km for every 10 Ma, as revealed by Hawaii and Yellow Stone. The most convincing evidence against the mantle plume model for the Permian basaltic magmatism in the Beishan-Tianshan region is that the mafic-ultramafic rocks of a single intrusion or from a small area <20 km across have an age difference up to ~20 Ma. The U-Pb ages of zircon from two small mafic dike swarms which occur ~20 km apart in the Beishan area are  $280.5 \pm 2$  Ma for Podong and  $266.2 \pm 3.2$  Ma for Luodong. The Podong mafic dikes are characterized by flat mantle-normalized REE patterns, moderately negative Nb anomalies and positive  $\epsilon_{Nd}(t)$  values from 5.5 to 7.5, which are similar to most of the Permian mafic-ultramafic intrusions in the Beishan and Tianshan regions. In contrast, the Luodong mafic dikes are characterized by significant enrichments in light REE, pronounced negative Nb anomalies, and lower  $\epsilon_{Nd}(t)$  values (-1.2 to 2.6) coupled by higher initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios. The different geochemical signatures for the two different dike swarms can be explained by different degrees of crustal contamination and source variations. Given a post-subduction environment for the Beishan-Tianshan region in the Permian based on geological records, we propose that the Luodong dikes are the products of melts generated by damp melting of delaminating, previously metasomatized lithospheric mantle, followed by significant crustal contamination during magma ascent, and that the Podong mafic dikes plus the mafic-ultramafic intrusions in the region are the products of melts generated by decompressed melting of upwelling asthenosphere, followed by minor crustal contamination during magma ascent.

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# **Mineralogical and petrographical characterization of Ni-Cu-(PGE)-enriched gabbroic dikes from the Hohwald (Lusatian Block, Bohemian Massif, Germany)**

by

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Mineralogical and petrographical characterizations have been performed on samples of five gabbroic dikes from the Hohwald area, localized 35 km east of Dresden (Saxony/Germany) within the Lusatian Highlands. The dikes were emplaced within Cadomian granodiorites of the Lusatian Block (Bohemian Massif) and belong to a Paleozoic predominantly WNW-ESE striking swarm-like dike generation. The Hohwald is in close vicinity (ca. 10 km W) to a Ni-Cu-(PGE)-bearing dike (Sohland-Rožany [DE/CZ]), which represents probably the same magmatic pulse and has been mined for Ni and Cu at the beginning of the 20th century. According to modal mineralogy determined with SEM-MLA, the samples can be subdivided into four general rock types: olivine gabbro, gabbro, gabbro and diorite. This study shows that samples of one dike can vary in their mineral content and petrographic properties among each other, mainly caused by the heterogeneity of the dikes.

Except for the diorites all samples display ophitic to subophitic textures. Modal compositions, determined by SEM-MLA, reveal 30-60 vol.% plagioclase, 15-25 vol.% clinopyroxene, 2-20 vol.% orthopyroxene, 1-30 vol.% olivine and < 15 vol.% amphibole + biotite for the olivine gabbros, gabbros and gabbros. The diorite is composed of 25 vol.% plagioclase, 35 vol.% amphibole, 10 vol.% clinopyroxene, 10 vol.% chlorite and 5 vol.% biotite.

A slight saussuritization of plagioclase and a considerable uralitization of clinopyroxene to green amphibole indicate a late-stage magmatic-hydrothermal alteration stage during the cooling of the magma. Latter alterations occur heterogeneously in the samples and range from an initial alteration along grain boundaries and cracks to an almost complete pseudomorphic replacement. SEM-EDX analyses show that clinopyroxene can usually be identified as augite and pigeonite. Orthopyroxene is mostly Mg-dominated. Olivines of the olivine gabbro feature a balanced Mg/Fe ratio, while gabbros and gabbros contain small amounts of Fe-dominated olivine. Furthermore, most of the olivine grains in the latter samples are characterized by severe alteration. They are predominantly altered to orthopyroxene + magnetite, whereas alteration to iddingsite and kelyphite occur subordinately. Magnetite and ilmenite appear in all samples. Magnetite generally shows lamellar exsolutions of ilmenite. The olivine gabbros and gabbros feature small amounts of fine-grained pyrrhotite-pentlandite-chalcopyrite aggregates. Additionally, accessory amounts of fine-grained altaite, hessite and Pd-Bi-tellurides, identified by SEM-EDX analyses, display also a PGE potential for these rock types. Larger sulfide accumulations (pyrrhotite-dominated disseminated + massive ore) occur in the olivine gabbroic Grenzland-I dike (> 250 m strike, 80-140 m width).

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## Continental-scale mapping of Ni-Cu-PGE mineral system potential of Australia

by

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Tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits contribute significant proportions of the world's production of Ni and PGEs, and represent some of the most valuable mineral deposits on Earth. However, there are very few known tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia, and these are mostly uneconomic due to small size, low grade and/or remoteness. Here we report results of a continental-scale study of the potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in Australia, the first to apply a mineral systems-based GIS prospectivity analysis at this scale.

The aim was to address whether the apparent under-representation of resources of this type in Australia is due to lack of geological endowment or is a consequence of concealment of mineral deposits by cover, which has hindered exploration success. It is generally accepted that major Ni-Cu-PGE sulfide deposits are consequences of lithospheric-scale earth processes. Ore formation requires four components of the mineral systems, namely: (1) energy sources/drivers of the ore-forming system; (2) favourable crustal and mantle lithospheric architecture; (3) sources of ore metals; and (4) gradients in ore depositional physico-chemical parameters. Conceptual criteria were developed that represent essential geological processes involved in each of the four components of the mineral system. These were translated into mappable criteria for which proxy geoscientific datasets were developed. Maps of favourability were constructed for each of the four system components. These were created using overlays of input rasters that were weighted (using a fuzzy logic-based method) according to the perceived importance, applicability and confidence level of each input dataset in the mineral system analysis.

The results for the four maps were allowed to contribute equally to the final mineral potential map so that the areas of highest potential represent targets where all four mineral system components combine most favourably. The GIS analysis of prospectivity uses a wide range of existing and newly developed continental- to regional-scale geological, geophysical and geochemical datasets, excluding known deposits. The assessment predicts high potential for tholeiitic intrusion-hosted Ni-Cu-PGE sulfide deposits in regions with known deposits while also highlighting several new prospective greenfield regions. The results strongly suggest that the current deficit of large economic deposits of tholeiitic intrusion-hosted Ni-Cu-PGE sulfides in Australia is due not to a lack of geologically favourable settings but is likely an apparent deficit due to difficulties in discovering such deposits in greenfield regions.

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# **Sulfur isotope studies of Ni-Cu-PGE sulfide mineralization hosted in metasedimentary country rocks of the Midcontinent Rift System and the Stillwater Complex, USA**

by

**Joshua Smith, Derek Prokopf, Edward Ripley, Chusi Li**

Country rock-hosted Ni-Cu-PGE massive sulfides are associated with mineralized mafic intrusions of the 1.1 Ga Midcontinent Rift System and the 2.7 Ga Stillwater Complex. Massive sulfides occur in metasedimentary country rocks beneath the Duluth Complex and the Stillwater Complex. Massive sulfides are present within the conduit-style Eagle and Tamarack intrusions, as well as within the country rocks. Locally, the intrusions and the massive sulfides are separated by several meters of country rock, and an igneous origin for these massive sulfides is not intuitive. Country rock-hosted massive sulfides may have leaked from the main intrusions, or formed by other igneous, hydrothermal, or sedimentary processes.

Here we report traditional and multiple sulfur isotope ratios of country rock-hosted mineralization. Massive sulfides beneath the Duluth Complex have  $\delta^{34}\text{S}$  values from 10.2-17.4 ‰, while igneous rock-hosted mineralization has values from 6.0 to 13.0 ‰. Massive sulfides in country rocks from Eagle have  $\delta^{34}\text{S}$  values between 2.6 to 3.6 ‰, and disseminated and net-textured mineralization have values from 0.3 to 4.6 ‰. Country rock-hosted massive sulfides at Tamarack have  $\delta^{34}\text{S}$  values from 0.5 to 2.5 ‰, and igneous-hosted mineralization has  $\delta^{34}\text{S}$  values from -0.2 to 2.8 ‰. At Stillwater, massive sulfides and the J-M reef have  $\delta^{34}\text{S}$  values around 0 ‰. Massive sulfides have  $\Delta^{33}\text{S}$  values from -0.13 to 0.47 ‰, and the J-M reef has  $\Delta^{33}\text{S}$  values from 0.012 to 0.068 ‰. Massive sulfides from Eagle and Tamarack have  $\delta^{34}\text{S}$  values similar to those of the igneous rock-hosted mineralization, but massive sulfides beneath the Duluth Complex have  $\delta^{34}\text{S}$  values that may be more  $^{34}\text{S}$ -enriched than the igneous-hosted mineralization. At Stillwater,  $\Delta^{33}\text{S}$  values suggest Archean S was incorporated into the massive sulfides.

Country rock-hosted massive sulfides from Tamarack and Eagle appear to represent sulfides that leaked from the conduits, through unidentified plumbing systems. The massive sulfides beneath the Duluth Complex required input of sedimentary S, although future work will help determine whether this was by direct incorporation into the parental magma and leaking of the sulfides, or by partial melting of sulfidic country rocks.  $\Delta^{33}\text{S}$  values from Stillwater suggest the massive sulfides were not formed by leaking of magma associated with the J-M reef, but may represent leaking of other magmatic pulses, sedimentary sulfides, or partial melting of country rocks. Additional S, Cu, and Os isotope studies are also in progress to help determine the origin of the country rock-hosted sulfide mineralization.

# The temperature and volatile contents of mantle derived magmas

by

Alexander Sobolev<sup>1,2</sup>, Valentina Batanova<sup>1,2</sup>

The compositional and thermal heterogeneity of convecting mantle critically affect magma production and compositions and cannot be easily distinguished from each other. The way to resolve this ambiguity is an independent estimation of temperature and composition of mantle sources of various types of magma.

Here we report application of olivine-spinel-melt geothermometers based on partition of Al, Cr, Sc, Y, Fe and Mg as well as direct measurement of H<sub>2</sub>O, S and Cl concentrations in olivine hosted melt inclusions from different primitive lavas of MORB, OIB, LIP, Archean komatiites and SSZ. The results suggest significant variations of crystallization temperature for the same Fo of high magnesium olivines from different types of mantle-derived magmas: from the lowest (down to 1220°C) for MORB and SSZ to the highest (up to over 1500°C) for komatiites and Siberian meimechites. These results confirm the relatively low temperature of the mantle source of MORB and SSZ magmas, low to moderate original amount of H<sub>2</sub>O in komatiites, high H<sub>2</sub>O contents of SSZ magmas and higher temperatures in the mantle plumes.

The established liquidus temperatures and compositions of primary melts allow estimating potential temperatures of their mantle sources. The highest potential temperatures over 1800°C are characteristic for Archean komatiites. For Phanerozoic age the highest potential temperatures (1650°C) are found for the largest LIPs: Siberian, North Atlantic and Caribbean. The sources of OIBs yield significant range of potential temperatures: 1400-1600°C, positively correlated with magma production rate. MORBs yield potential temperature between 1350-1400°C except those from ultra slow spreading ridges (e.g. Knipovich ridge), which display potential temperatures down to 1250°C. Potential temperatures of SSZ mantle sources are typically within the range for MORB, suggesting origin of SSZ primary melts by H<sub>2</sub>O fluxing of convecting mantle wedge. Exceptions are some boninites, which require higher temperature and plume related sources.

The results strongly confirm mantle plume theory and external source of H<sub>2</sub>O in SSZ mantle. The H<sub>2</sub>O in komatiites could be incorporated in the transitional zone. The S contents of most studied primary mantle derived melts are below sulfide saturation level at low pressures. The exceptions are primary melts of MORBs and some highly enriched melts- products of low degrees melting of mantle source (e.g. Siberian meimechites), which are close to sulfide saturation.

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# The newly found giant Early Devonian Xiarihamu Ni-Co sulfide deposit in northern Tibet Plateau, China

by

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The Xiarihamu Ni-Co deposit was discovered in the East Kunlun Orogenic Belt, northern Tibet Plateau, NW China. It is the secondary largest Ni deposit in China and contains ~157 million tonnes sulfide ores with average grades of 0.65 wt% Ni, 0.14 wt% Cu and 0.013 wt% Co. The main ore body being hosted in the ultramafic portion, which composes of olivine orthopyroxenite, orthopyroxenite and websterite. The zircons separated from the gabbronorite and websterite of the intrusion yield SHRIMP U-Pb ages of  $405.5 \pm 2.7$  and  $406.1 \pm 2.7$  Ma, indicating a genetic linkage with the Early Devonian post-subduction magmatism (400-410 Ma). The main ore body includes two large ore pods. The smaller one in the west comprises of disseminated sulfides hosted by olivine orthopyroxenite and orthopyroxenite; the larger one in the east consists of net-textured and disseminated sulfides hosted by orthopyroxenite.

The distribution and shape of the ore pods are well conformable with the undulating roof and bottom of the ultramafic portion, indicating great impacts geometry of the magma chamber on deposition of the sulfides. Another important characteristic of the sulfide ores is unusually high Ni/Cu ratios (~4–18), although PGE tenors of the ores are extremely low ( $< 4$  ppb Ir,  $< 85$  ppb Pt and  $< 115$  ppb Pd).

Song et al. (2016) proposed (1) the formation of the deposit is only associated with ultramafic portion, which was resulted from two pulses of magmas containing sulfide droplets; (2) the magma entered the magma chamber from the west; (3) the magmas were derived from low degrees of partial melting of an unusual pyroxenite mantle source formed by metasomatism of melt or fluid from subduction slab.

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## **Tectonic setting of Ni–Cu mineralization in the Fraser Zone, Albany–Fraser Orogen, Western Australia**

by

**Catherine V. Spaggiari<sup>1</sup>, Hugh Smithies<sup>1</sup>, Chris L. Kirkland<sup>2</sup>**

The Fraser Zone is an approximately 425 km long and 50 km wide, geophysically and structurally defined zone hosting predominantly granulite facies sills of non-cumulate gabbro and mafic to ultramafic cumulate bodies, coeval with granitic intrusions. These intrusions formed within modified crust of the southeastern margin of the Archean Yilgarn Craton between 1305 and 1290 Ma, within the Albany–Fraser Orogen, and were emplaced into sedimentary rocks of the Arid Basin. Previously considered unprospective, exploration for Ni–Cu sulfides in the Fraser Zone increased significantly following the discovery of the 14.6 Mt Nova–Bollinger deposit in 2012–13, hosted in interlayered gabbroic and peridotitic cumulates.

Since 2008, GSWA's regional mapping program in the Fraser Zone and surrounding regions has analysed field, geophysical data, over 150 geochemistry samples from both outcrop and drill cores, and regional geochronology and other isotope data. The integration of these datasets has revolutionized our understanding of the tectonic setting of the Fraser Zone, and is fundamental to models of ore deposit formation. Of particular significance are Nd isotope, zircon Hf isotope, and trace element systematics that show that mafic rocks of the Fraser Zone were mantle melts contaminated with small amounts of crust whose composition is consistent with modified Archean Yilgarn crust and Arid Basin sedimentary rocks. Structural observations reveal two folding events, the second coupled with the formation of orogen-parallel boudins and significant transposition of layering during high temperature metamorphism. Intrusion pulses punctuate this structural history. This suggests a hot, dynamic setting where magma emplacement was related to strain partitioning and localization, accompanied by fluid flow. Deformation may have affected intrusion timing, and stretching and pull-apart transposition may have been important factors in controlling sill size, type, and emplacement level.

The 1815–1140 Ma history of craton margin reworking recorded in the Albany–Fraser Orogen was dominated by extensional processes, which facilitated melting of Archean crust, coupled with additions of juvenile asthenospheric material. The hot dynamic setting responsible for formation of the Fraser Zone is interpreted to have followed oceanic-arc accretion to the passive margin of the orogen to the southeast, and can be interpreted as a response to orogenic collapse. This is consistent with the systematic migration of granitic intrusions from southeast to northwest, culminating with a large mantle upwelling and production of the Fraser Zone pinned against a major structure separating thick Yilgarn lithosphere from more substantially reworked and hyper-extended Yilgarn crust.

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# Geology and genesis of Fe-Ni-Cu-(PGE) mineralization in the Black Label Hybrid Zone of the 2.7 Ga Black Thor Intrusive Complex, McFaulds Lake greenstone Belt, Ontario, Canada

by

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The 2.7 Ga Black Thor Intrusive Complex (BTIC) is a >5 km long, ~1.5 km thick, >1 km wide (open at depth) layered intrusion that has been rotated to a sub-vertical orientation and is composed of dunite, ilherzolite, olivine websterite, websterite, and chromitite overlain by lesser gabbro and anorthosite. All lithologies have been metamorphosed to lower greenschist facies but most contain well-preserved igneous textures, which contain relict igneous chromite, pyroxene, and olivine. After emplacement but before complete crystallization, a petrogenetically-related Late Websterite Intrusion (LWI) reactivated the feeder conduit invading the lower and central part of the BTIC, including the Black Label Chromitite Zone (BLCZ) and Black Thor Chromite Zone (BTCZ). Field and petrographic examination shows that the LWI magma disaggregated and partially assimilated parts of the BLCZ producing marginal zones of heterogeneous, interfingering hybrid LWI matrix with variably sized (<2m, rarely > 5m) ilherzolite/dunite/chromitite inclusions and chromite/olivine xenocrysts, defined as the Black Label Hybrid Zone (BLHZ). The BLHZ contains 5-20% patchy disseminated to patchy net-textured Fe-Ni-Cu-(PGE) sulfide mineralization that is spatially restricted to the hybrid zones with no sulfide in adjacent inclusion-poor LWI or in unbrecciated BLCZ. Sulfide preferentially wets olivine relative to pyroxene with interfacial angles ranging 20-55°, mainly 25-35° (olivine) and 75-95° (pyroxene). The low interfacial angles for olivine suggest a relatively high  $fO_2$  within the system. Although the BTIC contains basal concentrations of Fe-Ni-Cu-(PGE) sulfides (e.g., AT-12, AT-12 Extension, and Contact Zone, and the larger Eagle's Nest deposit), only the most fractionated interstitial phases of the LWI contain minor Fe-Ni-Cu-(PGE) sulfides (i.e., it was not saturated in sulfide on emplacement). The BLCZ contains anomalous PGE-Cu-Ni, but only small amount of sulfides. The relatively high (normal) PGE contents of the mineralization in the BLHZ indicate that the LWI magma had not previously segregated sulfides. The restriction of sulfide mineralization to the BLHZ indicates that it formed during partial melting and assimilation of the BLCZ by the LWI, where Fe-Ni-Cu-(PGE) sulfides were generated by decreasing sulfide solubility when the more evolved LWI magma incorporated cumulate rocks formed by the more primitive phase of the magma that formed the BTIC. Although there have been many models proposed for the generation of Fe-Ni-Cu-(PGE) sulfides by magma mixing and magma contamination by country rocks, this appears to be one of the first examples of mineralization generated by contamination of a magma by cognate xenoliths and xenocrysts.

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## PGE-(Ni-Cu) mineralisation at Dablo, Burkina Faso

by

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The Dablo North PGE (Ni-Cu) occurrence is located within the northern area of the Dablo Main intrusion (“DMI”) in north central Burkina Faso. The DMI is an elongate 6 km long and up to 500 meters wide ultramafic-mafic intrusion that is part of a larger early Birimian-aged (2100-2200 Ma) magmatic event. The DMI intrudes into a mostly clastic sedimentary sequence with minor volcanics associated with the Bouroum Greenstone Belt.

Based on limited diamond drilling at Dablo North, the dominant rock types are (1) medium to coarse-grained harzburgite with between 50-70% olivine and up to 2 cm orthopyroxene oikocrysts, and (2) olivine pyroxenite to olivine melagabbro, mostly coarse-grained with 10-40% olivine and 60-90% orthopyroxenes, clinopyroxenes and lesser plagioclase. Both these lithologies are mineralized.

The PGE-(Ni-Cu) mineralisation is associated with disseminated to patchy sulfides, with lesser sulfide veinlets and local small blebs. The first 20 meters contain supergene mineralisation in the form of malachite and garnierite as disseminations and veinlets. Sulfides were observed below the weathered zone. QEMSCAN analysis (SGS, Lakefield) has identified pyrrhotite, pentlandite, pyrite, cubanite and chalcopyrite as the main sulfide minerals. A large number and a wide variety of PGM were identified including: sperrylite, moncheite, merenskyite, insizwaite, irarsite, mertierite, testibiopalladinite and kotulskite. The PGM grains varies from <1 to 15 µm in size. Electrum, kustelite and petzite (Au-minerals) have also been identified.

Multiple PGE-(Ni-Cu) rich sulfide-bearing horizons have been recognised in drill core. The mineralized horizons are not confined to a single lithological unit but are associated with harzburgite and olivine pyroxenite. The mineralization is accompanied by shifts in Cr abundances and changes in olivine morphology (from rounded cumulate textures to more amoeboidal intergrown textures potentially indicated disequilibrium) likely as the result of new magma influxes.

Downhole geochemical profiles for a range of elements including Mg, Cr, Al, Ca, Ti and Zr display both fractionation and fractionation reversals. This infers both fractionation within individual pulses and the introduction of new magma pulses. Using modal forsterite calculations, the parental magma for the DMI intrusion was estimated to be komatiitic basalt with an MgO content of 16 wt%. Pd/Ir ratios are typical for High MgO basalts, consistent with the estimated primitive parental magma. The mineralisation observed at Dablo North shows a strong sulfide control, with high Ni, Cu and PGE tenors. Tenors are moderately consistent between the different horizons implying a homogeneous source.

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# **Evidence of thermomechanical erosion of basalt by Fe-Ni-Cu sulfide melt at Kambalda**

by

**Sebastian Staude<sup>1</sup>, Margaux Le Vaillant<sup>2</sup>, Stephen J. Barnes<sup>2</sup>**

Thermomechanical erosion beneath lava flows has been observed in real time beneath active basalt lava tubes. In ancient lava flows direct measurements are not possible and one has to find other evidence. In komatiite lava flows thermomechanical erosion produced channels and embayments therein where Ni-bearing sulfide magmas accumulated to form important Ni deposits. Direct field evidence for thermomechanical erosion in these settings is rare and includes stratigraphic relationships and magmatic ferrichromite aligned along erosional contacts. Due to the scarcity of well-preserved textural evidence of the contacts themselves, several other theories have been developed to explain the embayments in the past, including a purely tectonic origin.

In the well-preserved komatiite-hosted Moran deposit (Kambalda, Western Australia) several types of textures have been preserved along the host basalt - sulphide contact. These include melt-induced fractures and breccias, ocellar basalt with composite sulphide globules, basalt sulfide emulsions, basalt plumes rising into sulfides and plates of partly detached basalt rising into sulfides on the basal contact, all of them containing skeletal ferrichromite produced by reaction between silicate and sulfide melts. In areas where the sulfide melt infiltrated sideways into the host basalt (called pinchouts) the upper contact is characterised by amphibole-chromite intergrowth and frequently hosts a layer of solidified molten basalt scum. The solidified basalt scum is characterised by frequent segregation vesicles and common basalt-sulfide emulsions.

Combining all the textures one can reconstruct the processes involved to create the Ni-hosting embayments. Sulfide melt infiltrates and partly creates its own fractures in the basalt underneath. Small amounts of the basalt in the immediate vicinity are melted and forms a thin chromite-decorated melt film on the contact. This melt film increases in thickness over time and becomes unstable forming plume-like textures rising into the sulfides. Once this plume becomes too large, it detaches and float through the sulphide melt. In pinchouts the detached basalt drops are trapped underneath the upper solid basalt forming the floating basalt scum layer above the sulfides. Increasing amounts of detached basalt drops result in an overflow of the capacity that the pinchout is able to hold. These overflow areas experienced a relatively high basalt flow velocity along the basalt sulfide interfaces, resulting in the formation of basalt sulfide emulsions. Lateral erosion by the sulfide melt to form pinchouts is favoured by the capability of the sulfide pool to transfer heat to the overlying basalt roof once the pinchouts have become established.

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## First underground geological observations at the Nova-Bollinger Ni-Cu-Co-sulfide deposit, Fraser Range, Western Australia

by

Sebastian Staude<sup>1\*</sup>, David Hammond<sup>1</sup>, Jon Chapman<sup>1</sup>, Andy Thompson<sup>1</sup>

The Nova-Bollinger Ni-Cu-Co sulfide deposit is situated in the 1.3 Ga Fraser Zone of the Albany-Fraser Orogen in the south of Western Australia. Sulfide mineralization occurs on the base of a mafic-ultramafic intrusion, which is hosted by granulite-facies metasediments, and mafic and felsic metamagmatic rocks.

Nova was discovered in 2012 by Sirius Resources and was extended by the discovery of Bollinger in February 2013. The mineral resource in July 2014 was estimated to be 14.3Mt with 2.3% Ni, 0.9% Cu, and 0.08% Co at a contained metal of 325,000t of Ni, 134,000t of Cu, and 11,000t of Co. The project was acquired by IGO in September 2015. Underground mining started in May 2015 with the first ore intersection in May 2016. We present here the first geological observations of this new magmatic Ni-sulfide deposit from underground mining.

The host package intersected in the Nova decline is composed of quartz-biotite-garnet ( $\pm$ graphite) gneiss (kinzigite), calcite-olivine-pyroxene marble, felsic orthogneiss, and quartz-pyroxene-garnet granulite. All of these rocks have variable proportions of each mineral. The high-temperature metamorphism is not indicated by typical minerals stable at these conditions (e.g., sillimanite, cordierite, sapphirine) but by frequently observed migmatitic textures in mafic gneiss. The only high-pressure indication is the occurrence of kyanite in quartz-garnet dominated gneiss.

The entire stratigraphy was folded and the Nova deposit is now situated in a bowl-like fold structure (visible by electromagnetics on surface due to high-magnetic rocks as 'The Eye'). A charnockitic melt intruded into the stratigraphy outside the bowl forming a large homogeneous intrusive body at the start of the decline and thin dykes closer towards the bowl. At least two batches of mafic and ultramafic melt intruded into the bowl forming two intrusions separated by carbonate-rich metasediments. Close to the mafic-ultramafic intrusion several dykes and pegmatites of anorthosites are observed cutting through the metamorphic foliation. Sulfides are hosted by pyroxenite, norites to leuconorites, and anorthosites and are observed as infiltration within the metasedimentary foliation, breccia sulfides (massive sulfides with frequent clasts of variable size of biotite, feldspar and garnet), matrix sulfides and disseminated sulfides. Blebby disseminated sulfides are observed in younger leuconorite cutting through older rocks. Sulfides comprise pyrrhotite, pentlandite and chalcopyrite. In massive sulfide and sulfide veins large (several centimetre) crystals of pyrrhotite are surrounded by pentlandite and chalcopyrite.

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# Decoupling of the Re-Os and S isotopic systems in the PGE-depleted Ni-Cu sulfide deposits: insight for the role of crustal sulfur in sulfide saturation

by

Bo Wei<sup>1\*</sup>, Christina Yan Wang<sup>1</sup>, Yann Lahaye<sup>2</sup>

A number of Permian-Triassic magmatic Ni-Cu sulfide deposits have been discovered in the central Asian orogenic belt (CAOB) in China. The host mafic-ultramafic intrusions of the deposits contain abundant orthopyroxene and have negative Nb anomalies on the primitive mantle-normalized trace element patterns. The sulfide ores of the deposits have total PGE concentrations < 0.5 ppm and small variations of  $\epsilon\text{Nd}$  values (within three units) against highly variable  $\gamma\text{Os}$  values (+35 to +273). The latter observation is attributed to the addition of external crustal sulfur in the magmas of the deposits in previous studies.

However, in this study, in situ S isotopic analyses on the sulfides of the sulfide ores from three Ni-Cu sulfide deposits and the country rocks of the host intrusions in CAOB show that the sulfides have  $\delta^{34}\text{S}$  values ranging from -1.0 to +1.1 ‰, close to the mantle values of  $0 \pm 2.0$  ‰, whereas the country rocks have  $\delta^{34}\text{S}$  values ranging from -1.5 to -19.3 ‰. Therefore, we argue for a mantle-derived sulfur source in these deposits

rather than the addition of external crustal sulfur. The reason why these deposits have high and variable  $\gamma\text{Os}$  values is because the parental magma is PGE-depleted. A PGE-depleted magma likely contains extremely low Os, so that the Re-Os system of the magma is more susceptible to the addition of external crustal sulfur and is easily to be biased towards crustal signature. On the other hand, the mantle-like  $\delta^{34}\text{S}$  values of the sulfides indicate that significant modification of S isotope signatures of the magma may be only feasible by the involvement of high amounts of external crustal sulfur. In this case, the sulfide ores would have decoupled S and Re-Os isotopic compositions. This study indicates a combination of S, Sm-Nd and Re-Os isotopic systems provides a better way to evaluate the role of the crustal sulfur in the sulfide saturation of the magma, especially for PGE-depleted Ni-Cu sulfide deposits.

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## Hyperspectral imaging of Ni grade variability in the Goro Nickel Deposit (New Caledonia)

by

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New Caledonian lateritic nickel deposits are typically characterised by Ni mineralisation occurring as either oxide type or 'garnieritic' type deposits. The Goro nickel deposit consists of an upper goethite-rich Ni zone ('yellow laterite') overlying a hydrous, Mg-Ni-silicate ('saproilitic') zone. Significant vertical variation in Ni grade in the oxide zone may be linked to 'ageing' processes related to goethite recrystallisation in response to the in situ weathering intensity as a function of depth in the profile.

Reflectance spectroscopy can be used for advanced resource characterisation by improving the delineation of ore-body stratigraphy and in mapping the mineralogical distribution. The common goethite varieties, ochreous (OG) and vitreous goethite (VG), are spectrally distinct in the visible to near-infrared wavelength (380–1100 nm) range, and can be routinely identified in drill core and RC chips. OG shows a relatively sharp and symmetric crystal field absorption feature at  $\approx 900$  nm (CFA900), whereas the CFA900 feature for VG is comparatively broad and asymmetric. The full width half maximum (FWHM) of the CFA900 feature was used as a spectral index to identify and quantify OG (FWHM value of  $\approx 1.1$ – $1.2$ ) and VG (FWHM value is  $\approx 1.25$ – $1.4$ ).

A combination of reflectance hyperspectral imaging, X-ray diffraction (XRD) and bulk compositional analyses characterised the variations in Ni grade and goethite crystallinity with depth (0–52 m) in the Goro Ni laterite profile. Bulk compositional analysis confirmed that Ni grade increased from 0.54 % to 2.92 % with depth. Goethite XRD FWHM values increased from  $\approx 0.4^\circ$   $2\theta$  at the surface to  $\approx 1.2^\circ$   $2\theta$  at  $\approx 25$ – $26$  m depth, indicating a decrease in goethite crystallinity. At greater depths, the XRD FWHM remained relatively constant at  $\approx 1.2^\circ$   $2\theta$ , suggesting a limit of stability to the goethite structure. As a mirror-image response, CFA900 FWHM values decreased from  $\approx 325$  nm at the surface to near constant widths of  $\approx 250$  nm at depths  $> \approx 25$ – $26$  m, with goethite changing from more vitreous to a consistent, ochreous spectral response deeper in the profile.

The findings of this work provide further insights into the effects of weathering processes that occur during formation of lateritic nickel deposits and demonstrate that variations in the Ni-grade of oxide deposits can easily and quickly be quantified using spectroscopic imaging techniques. This has implications in resource characterisation as rapid assessment of the variability in Ni-grade can assist with refining ore sorting methodologies to better optimise processing performance.

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## Multiple S isotope studies of PGE enrichment in the J-M Reef, Stillwater Complex, Montana, USA

by

Benjamin W. Wernette, Edward M. Ripley, Chusi Li, Joshua Smith, Ben Underwood, Annie Ayre

The J-M Reef in the 2.7 Ga Stillwater Complex averages ~ 14 ppm Pd and 5 ppm Pt. R-factor calculations using D values for Pd of ~  $5 \times 10^5$  indicate that to account for the Pd content of the sulfides in the Reef, R-factors exceeding ~  $5 \times 10^5$  would be required. A magma column of ~ 1400 m would be necessary to supply the Pd if the magma contained 10 ppb Pd. Open system processes of PGE concentration have been proposed to account for the emplacement of PGE-enriched melts where such high R-factors would not be required. Researchers have proposed that the addition of crustal S to staging chambers beneath the Complex allowed for concentration of PGEs and the generation of PGE-rich magmas. Because  $\delta^{34}\text{S}$  values alone may not provide information on the role of crustal sulfide addition in Archean magmas, a study of multiple S isotopes was initiated.

Sulfur from both massive and disseminated sulfides in metasedimentary rocks beneath the Stillwater Complex show  $\Delta^{33}\text{S}$  ( $\Delta^{33}\text{S} = \delta^{33}\text{S} - 1000 \times [(1 + \delta^{34}\text{S}/1000)^{0.515} - 1]$ ) values that range between 0.32 and 0.23 ‰.  $\delta^{34}\text{S}$  values vary between -1.4 and 5.8 ‰. Samples of the J-M Reef have  $\Delta^{33}\text{S}$  values between 0.05 and -0.005, and  $\delta^{34}\text{S}$  values generally between -0.9 and 0.6 ‰. However, a small number of Reef samples show  $\delta^{34}\text{S}$  values between 3 and 6 ‰.

$\Delta^{33}\text{S}$  values and  $\delta^{34}\text{S}$  values near 0 ‰ are not supportive of the addition of crustal S to magmas that generated the J-M Reef. However, the presence of anomalous  $\delta^{34}\text{S}$  values indicates that, at least locally, crustal S was incorporated into the Reef rocks. This interpretation is consistent with the variable spatial distribution of sulfides in the multiple lithologies of the Reef. Although  $\Delta^{33}\text{S}$  values of the Reef can be produced by mixing of the two principal populations found in the metasedimentary hornfels, the  $\delta^{34}\text{S}$  values of the two populations precludes such an interpretation. Multiple pulses of sulfide-saturated magmas were involved in the production of the J-M Reef, but only sporadic high  $\delta^{34}\text{S}$  values suggest that crustal S may have played a local role in promoting sulfide saturation and potential PGE enrichment.

## **A subduction-related magmatic Ni-Cu-(PGE) deposit at southern margin of the Central Asian Orogenic Belt, NW China, geochemical features and implications**

by

**Wen-Qin Zheng<sup>1</sup>, Wei Xie<sup>1,2</sup>, Xie-Yan Song<sup>1</sup>**

The Heishan Ni-Cu-(PGE) deposit, containing ~35 million tonnes of disseminated sulfide mineralisation with average grades of 0.6 wt.% Ni and 0.3 wt.% Cu, is located at the southern margin of the Central Asian Orogenic Belt. The intrusion hosting the deposit is emplaced in Neoproterozoic metamorphic rocks. There are two ore bodies (No. 1 and No. 4) within the harzburgite and lherzolite at the lower part of the intrusion. The sulfides of the No. 4 ore body are lower in PGE (on the basis of 100% sulphide; 580-1,860 ppb Pt, 720-1,450 ppb Pd, 50-120 ppb Ir) and higher in Cu/Pd ratios (48,000-75,000) than the sulfides of the No. 1 ore body and mineralised harzburgites, which have 2,350-4,110 ppb Pt, 3,460-5,840 ppb Pd, 130-160 ppb Ir and Cu/Pd ratios of 16,000-26,000. We propose that the sulfide segregation of the No. 4 ore body was associated with extensive introduction of crustal sulphur, whereas low  $\delta^{34}\text{S}$  values (+0.43 - +1.01 ‰) and restricted range of Pd/Ir ratios indicate that the high PGE contents of the sulfides in the No. 1 ore body resulted from the reaction between the sulfides and new pulses of S-undersaturated magmas.

The dominant lithologies of the intrusion are harzburgite and lherzolite. Olivine gabbro-norite and gabbro dykes occur only along the southern margins of the intrusion. Zircon ID-TIMS U-Pb age data ( $356.4 \pm 0.6$  Ma and  $366.6 \pm 0.6$  Ma) and SHRIMP U-Pb age data ( $358 \pm 5$  Ma and  $357 \pm 4$  Ma) indicate that the intrusion was emplaced in the Late Devonian. Enrichments of large ion lithophile elements, strong negative Nb (Ta) anomalies and positive K and Pb anomalies are very similar to those of the Devonian volcanics in the Beishan Fold Belt, and indicate subduction-related magmatism. The high  $(^{207}\text{Pb}/^{204}\text{Pb})_t$  (15.55-15.64) and  $(^{208}\text{Pb}/^{204}\text{Pb})_t$  (37.71-38.29) values are comparable with those of the volcanics along the Pacific margin of America. We propose that the high-Mg basaltic magma was generated from partial melting of the asthenosphere and mantle wedge triggered by upwelling of the asthenosphere due to slab break-off in an active continental margin. The discovery of the Heishan deposit provides further evidence for the exploration potential for Ni-Cu-(PGE) sulfide deposits in subduction-related settings (Xie et al., 2012, 2014).

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# Simulation for the partitioning behaviour of Ni in the partial melting of mantle under various tectonic settings

by

Zhuo-sen Yao<sup>1,2</sup>, Ke-zhang Qin<sup>1</sup>

Partitioning of Ni during the partial melting of mantle exerts a critical control on the metal content of mantle-derived magma, and hence the ore potential of magmatic sulfide deposit. Variation of Ni content during mantle melting at constant pressure (isobaric melting) has been simulated. However, the high degree of isobaric melting requires the continuous increasing temperature, which mostly exceeds the threshold temperature offered by upper mantle. Moreover, the MgO content of magma is a function of temperature and pressure, but the isobaric calculation ignores the influence of pressure and generates an unreliable result of MgO. This definitely further affect the calculation of Ni content, because the Ni partition coefficient is a faction of MgO content in magma.

We model the continuous fractional melting of depleted MORB mantle at various potential temperatures ( $T_p$ ), water contents and fractions of remaining melt (porosity). It's found that high  $T_p$ , low porosity and high water can increase the Ni content of melt at the initial stage of melting. The Ni content will decrease with the increasing melting degree, which is attributed to the decreasing MgO during partial melting. Adiabatic decompression melting is the main process inferred in plume, and the modelling also shows the negative correlation between the Ni content of magma and melting degree. At the same pressure, a higher water content can cause a larger volume mantle melting, but lead a decrease in the Ni content of melt. It suggests that although the dehydration of lithospheric delamination induces large-scale magmatism, its contribution to Ni content in melt is negative.

When the ascent of mantle plume is obstruct by the overlying rigid lithosphere, the hot material will induce the partial melt of the colder SCLM. Isobaric melting is suitable in this case, but SCLM cannot hotter than the subjacent mantle plume at an appropriate range ( $T_p$ : 1500-1600°C). Thickness and evolution of lithosphere (A-SCLM, >2.5 Ga; P-SCLM, 2.5-1.0 Ga; T-SLM, <1.0 Ga) influence the Ni content of melt. In the magma mixed by mantle-lithosphere-interaction, the Ni content came from SCLM may be limited. We also tentatively simulate the flux-melting in mantle-wedge, generating a Ni-poor magma. The composition of slab fluid has little influence, and high temperature may slightly increase the Ni.

Our preliminary work reveal the portioning behaviour of Ni during mantle melting in various tectonic settings ( $Ni_{plume} \gg Ni_{MORB} \gg Ni_{Subduction}$ ), and update the understanding about Cu-Ni-ore-forming process of mafic-ultramafic magmas.

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## **Geometallurgy of low grade Ni sulphide deposits; challenges and success stories**

by

**Ben A. Grguric<sup>A,B</sup>**

Large-tonnage, low-grade Ni sulphide deposits represent important Ni producers in the Yilgarn of Western Australia, with production principally from the Mount Keith (MKD5) and Perseverance (Agnew) mines in the Agnew-Wiluna Belt. The principal mode of occurrence of Ni ( $\pm$ Fe) sulphides in these deposits is as disseminated blebs (0.1-5 mm) interstitial to former olivine cumulus crystals in serpentinised and talc-carbonate altered dunites and peridotites. The mineralogy and metallurgical properties of low-grade, disseminated ores are complex, and consequently have required detailed characterisation combined with innovative processing and grade control in order to achieve respectable metal recoveries and concentrate quality. Most of this complexity relates to the effects of hypogene and supergene alteration of the ultramafic protore, and consequent modification of both gangue and sulphide mineral assemblages. The hypogene alteration overprint on these ore systems is a double-edged sword. On the one hand the altered sulphide assemblages are typically very high tenor, in some cases in excess of 72% Ni (e.g. West Jordan), with the potential to yield high-grade concentrates. On the other hand the fine grainsize of the sulphide blebs and their intimate intergrowth with high-MgO gangue phases is problematic with regard to Ni recovery and concentrate 'smeltability'. The larger of the low-grade (Type 2) Ni sulphide deposits in the Agnew-Wiluna Belt were discovered in the period 1969-1971, however, production of Ni from these deposits was delayed for over 20 years due to a combination of metal recovery and concentrate quality issues, and inefficient truck technology at the time. A novel processing circuit incorporating 100's of desliming cyclones was designed and commissioned by WMC Resources in 1993-94 for the new Mount Keith plant, significantly reducing the problems associated with high pulp viscosities and reagent consumption. Even so, nameplate Ni recovery was not achieved at this plant without an aggressive campaign of recovery improvement projects. Careful grade control practices were implemented in order to reduce the deleterious effects of talc in flotation feed, a major problem later solved with a patented modification to the flotation conditions. High chlorine in concentrate was combatted with a novel ion exchange process, and arsenic penalties were reduced by careful ore and concentrate blending practices from a range of company-wide feed sources. One problem that still plagues Type 2 systems is the difficulty of smelting their concentrates due to their inherent low Fe:MgO ratio. This has spurred the development of hydrometallurgical concentrate treatments such as the Yakabindie Process and Activox.

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# Ni-Cu-PGE ore deposition driven by metasomatic fluids and melt-rock reactions into the deep crust

by

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The Valmaggia ultramafic pipe belongs to a group of Ni-Cu-PGE-rich, hydrous ultramafic intrusions emplaced within the Ivrea-Verbano Zone (Italy). According to the latest interpretation, these early Triassic ultramafic pipes belong to a network of magma conduits derived from partial melting of continental lithospheric mantle metasomatized by fluids and melts related to the Eo-Variscan subduction. The Valmaggia pipe bears evidence of the metasomatizing process to which Ni-Cu-PGE mineralization is related. The pipe consists of an early coarse-grained, anhydrous peridotite/pyroxenite assemblage with olivine, diopside, enstatite, Cr spinel extensively overprinted by the growth of metasomatic assemblage including Ti-rich pargasitic amphibole and phlogopite oikocrysts, Al-rich enstatite, Al spinel, Cl-F-rich apatite, carbonates and Fe-Ni-Cu sulfides. The pipe margins preferentially host the Ni-Cu sulfide mineralization occurring as enrichments of disseminated droplets, network-like aggregates and unusual coarse, cm-sized round to amoeboidal nodules. Ore minerals include PGE-bearing pyrrhotite/troilite and pentlandite, chalcopyrite, cubanite and accessory Ni-Pt-Pd and Ag-Bi-Pb tellurides, with magnetite and ilmenite. Sulfide enrichments closely follow the distribution of amphibole and other volatile-rich phases. The coarse-grained nodules are zoned with cores made of troilite-pyrrhotite  $\pm$  pentlandite and rims rich in pentlandite, chalcopyrite, magnetite and PGE tellurides, accompanied by sulfide mirmekites in enclosing silicates. Magmatic carbonates such as dolomite, calcite and Mn-siderite are commonly associated with sulfide nodules, forming impressive intergrowths along their embayed and cusped margins. The pipe is emplaced into the Main Gabbro of the Ivrea-Verbano Zone. Its margins develop “soft” contacts and pegmatoid pockets along metric lobes with a peculiar labradorite-biotite magma envelope (“plagioclasite”), embedding sulfide-bearing mafic enclaves of the pipe. The pipe contacts are marked by conspicuous pargasite-spinel symplectites by reaction between the ultramafic and the plagioclasite assemblages. Similar but more extensive reaction is recorded within the pipe where remnants of volatile-rich plagioclase melt infiltrating the anhydrous pyroxenite survived after producing the characteristic metasomatic sulfide-rich amphibole/phlogopite-dominated pipe association. Elaboration of reactants and products by *Perple\_X* provide an estimate of PT conditions for the metasomatic reaction ranging 750°-1000°C up to 8 kbar. A major role for fluids and a deep-crustal polyphase magmatic history are recorded by textures, assemblages and major to trace element signatures of mineral phases. In this framework, the ore forming process is linked to the metasomatic, fluid-driven melt-rock reaction where metal enrichment and emplacement of sulfide melt are promoted and controlled by volatiles (saline aqueous fluids and carbonic gas/melt).

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# Dyke tips and melt pathways: Insights from UAV Photogrammetry

by

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Alexander Cruden<sup>3</sup>, Marco Fiorentini<sup>1</sup>, and Eric Tohver<sup>1</sup>

In the context of intrusion-related magmatic sulfide deposits, structural culminations and perturbations are important sites for sulfide melt accumulation. Examples of mineralised culminations include tips of blade-shaped dykes (e.g. Expo intrusive suite, Raglan trend) and keels boat-shaped intrusions (Huangshandong, China). Sites of structural perturbation include step-overs in magma conduits (Discovery Hill dyke, Voisey's Bay) and dyke-sill transitions. Despite the recognition of structural controls on sulfide concentration, magma dynamics and conduit development remain poorly understood in the context of intrusion-related magmatic sulfide deposits. Physical processes of magma emplacement remain enigmatic in part because of limited exposure, post-emplacement deformation, or both. Studies of analogous structural culminations from well-exposed, non-deformed mafic intrusion networks yield insights relevant to emplacement processes and magma dynamics of mineralised systems. To understand conduit growth and magma migration we combine drone-based structural mapping with magnetic fabric analysis, detailed geochemical traverses, and microtomography. This integrated approach is applied to an exceptionally well-exposed suite of gabbroic dykes on south coast of Western Australia. The host rock is Proterozoic orthogneiss and monzogranite of the Albany-Fraser orogen. We map brittle deformation around dyke tips and step-over regions, showing that dyke tip geometry is related to fault-fracture networks developed ahead of the dyke propagation front. Dyke arrest and inflation accounts for the ingress of magma into late-forming faults at dyke tips. Faults and fractures developed around mafic dykes are potential traps for high density, low viscosity sulfide melt.

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