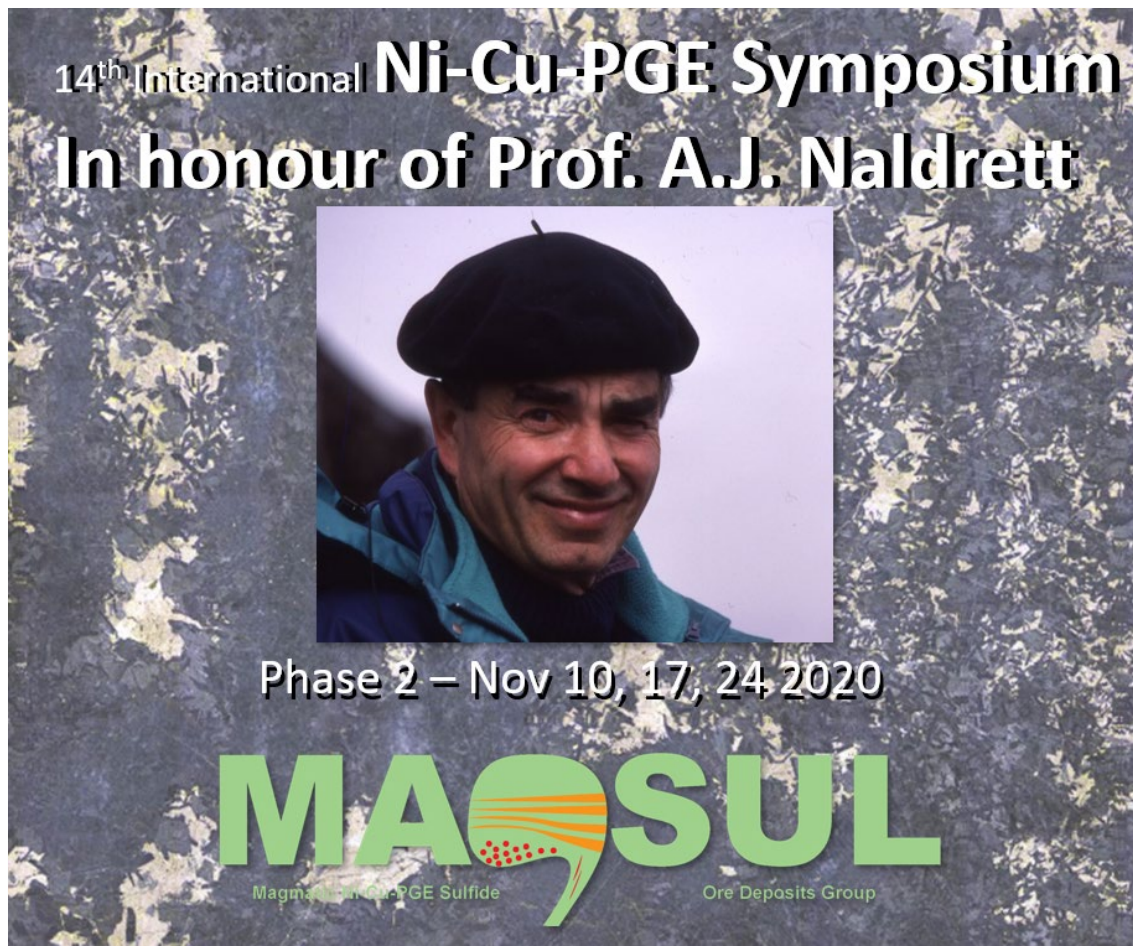


## 14th International Nickel Symposium and Naldrett Memorial

### ABSTRACT VOLUME AND PROGRAM



**VIRTUAL MEETING HELD 10<sup>TH</sup>, 17<sup>TH</sup>, 24<sup>TH</sup> and 25th NOVEMBER 2020**

**EDITORS (Phase 2): David Holwell, Steve Barnes, Maria Emilia Schutesky**

### ORGANIZING COMMITTEE

Sarah-Jane Barnes, Steve Barnes, David Holwell, Maria Emilia Schutesky,  
Michael Leshner, Wolfgang Maier, Eduardo Texeira Mansur

*Abstracts listed in order of presentation*

*Most presentations and the Virtual Field Trip will be available in video format  
post-conference from [www.magsul.org](http://www.magsul.org)*

## **10<sup>th</sup> November      Norilsk-Talnakh Ni-Cu-PGE Camp**

<i>Chair</i>		<i>Steve Barnes</i>
Time (UTC)	Speaker	Title
12:00	Steve Barnes	Opening/Introduction
<b>12:05</b>	<b>Yudovskaya M</b>	<b>Breccias of the Norilsk ore fields and their significance for interpretation of mineralization</b>
	<b>KEYNOTE</b>	
12:35	Beresford S	Role of hydrogeochemistry in the discovery of the Talnakh-Oktyabrsky Cu-Ni-PGE deposit: an historical account
12:50	Marfin A	S/Se Ratio of Sulfide Ores and Potential Crustal Contaminants of The Oktyabrsk Deposit, Norilsk-Talnakh Ore District (5 min. talk)
13:00	Malitch K	Origin of zircon from the Noril'sk-type economic intrusions: evidence from morphological, compositional and isotope data
13:15	Yao Z	Linking the Siberian flood basalts and Ni-Cu-PGE sulfide deposits at Noril'sk
13:30	Le Vaillant M	Understanding genetic processes at Norilsk by combining in-situ LA-ICP-MS and S isotopic data on different sulfide textures.
13:45	Iacono-Marziano G	The role of magma degassing in sulphide melt mobility and metal enrichment
14:00	Discussion	Questions to be posted in Chat

## **10<sup>th</sup> November      Layered Intrusions, PGE, Chromite**

<i>Chair</i>		<i>Steve Barnes</i>
14:20	Fiorentini M	A proposed genetic link between Proterozoic magmatism and metallogenesis in Australia and the Bushveld superplume
14:35	Smith W	Up close and personal with the Merensky Reef: insights from $\mu$ XRF and SEM mapping
14:50	Chaumba J	Petrology of the Zvishavane Ultramafic Complex, south-central Zimbabwe, and speculations on why it lacks platinum-group element mineralization
15:05	Heggie G	Chromite Mineralization and Igneous Stratigraphy of the Blackbird Deposit, Ring of Fire, Ontario, Canada
15:20	Discussion	Questions to be posted in Chat

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15:40 End of the session

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**17<sup>th</sup> November*****Intrusion emplacement****Chair**Maria Emilia Schutesky*Time  
(UTC)

Speaker

Title

12:00 Schutesky M. E. Welcome, introduction

12:05 **Magee C**  
**KEYNOTE** **Unravelling sill emplacement using 3D seismic reflection data: implications for mineralisation**

12:35 Kopping J.\* Geometry and emplacement of elongate, finger-like intrusions

12:50 Nissanka Arachchige U\* The effect of solidification on formation and propagation of finger-like conduits: An experimental approach with application to sulphide deposits

13:05 Thakurta J/ Rupp On the origin of a late gabbroic unit associated with the Eagle East ultramafic intrusion in Marquette County, Michigan, USA

13:20 Discussion Questions to be posted in Chat

13:40 End of the session

**17<sup>th</sup> November*****Magmatic Ni-Cu-Co sulfide deposits****Chair**David Holwell*
**13:40 Mungall J**  
**KEYNOTE** **Role of compound drops in magmas**

14:10 Martin L Potential origin(s) for garnet growth at silicate-sulphide contacts at Nova-Bollinger

14:25 Cherdantseva M Caught in the moment: CO<sub>2</sub>-rich fluid exsolution from magmatic sulfides in the middle crust

14:40 Evans D Chalcophile trace element indicators of sediment contamination at Muremera-Rujungu (Burundi) and Kabanga (Tanzania)

14:55 Blanks D\* Unravelling the crystallisation of Ni-Cu-PGE sulfide at Munali: evidence for Cu migration?

15:10 Virtanen V\* Complex effects of assimilation to sulphide saturation in the Duluth Complex, Minnesota, revealed by modeling with Magma Chamber Simulator

15:25 Staude S Sulfide evolution of the Moran komatiite-hosted Ni deposit, Kambalda, Western Australia

15:40 Discussion Questions to be posted in Chat

16:00 End of the session

<b>24<sup>th</sup> November</b>		<b>Unconventional Ni/PGE geochemistry</b>
<i>Chair</i>		<i>Margaux Le Vaillant</i>
Time (UTC)	Speaker	Title
12:00	Le Vaillant M	Welcome/Introduction
<b>12:05</b>	<b>Keays R</b> <b>KEYNOTE</b>	<b>The Avebury Nickel Deposit, Tasmania, Australia: New Insights into the Genesis of a Significant Unconventional Nickel Sulfide Deposit</b>
12:35	Anenburg M	TABS-sulfide liquid immiscibility and PGE nanonuggets
12:50	McFall K	What controls the PGE content of porphyry Cu deposits?
13:05	Mungall for Robb	Distribution of platinum group elements in the New Afton alkalic Cu-Au porphyry deposit, Kamloops, British Columbia
13:20	Discussion	Questions to be posted in Chat

<b>24<sup>th</sup> November</b>		<b>Unconventional Ni-Cu-PGE</b>
<i>Chair</i>		<i>Marco Fiorentini</i>
13:40	Garcia V	The Neoarchean GT-34 Ni deposit, Carajás Mineral Province, Brazil: an atypical IOCG-related Ni sulfide mineralization
13:55	Schutesky M	Unusual Ni sulfide deposits within the Neoarchean Carajás IOCG System – magmatic or hydrothermal?
14:10	Thompson J	Cu (Ni, Au, PGE) deposits of the Curaçá Valley – products of complex magmatic and post-magmatic processes?
14:25	Mungall J	Epigenetic hydrothermal Ni mineralization of the VW Zone, Junior Lake, Ontario, Canada
14:40	Discussion	Questions to be posted in Chat
15:00	End of the session	

<b>25<sup>th</sup> November</b>		<b>Virtual Field Trip</b>
12:00	Beach S	Virtual field trip to the Eagle Deposit

## Breccias of the Norilsk ore fields and their significance for interpretation of mineralization

Yudovskaya, M.A.<sup>1,2</sup> and Barnes S.J.<sup>3</sup>

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Magmatic breccia lays down strong constraints on interpretations of an order of geological events, reveals physical-rheological properties of both matrix and fragment's protholith, and may indicate ways of magma emplacement, stress and deformation. The primary classification of endogenous breccias is based on the inferred role of magma and/or fluids in breccia formation with magmatic, phreatomagmatic, phreatic and hydrothermal breccias recognised. Here we consider ore-related breccias of a magmatic origin that mark the different stages of the magmatic sulphide ore formation in the Norilsk ore fields. Lyulko et al. (1972) subdivided the Norilsk ore-related breccias into: i) intrusion breccia at the top of intrusions, ii) magmatic breccia at the base of intrusions, iii) breccias of the front of emplacement. We follow this classification albeit revising some connotations.

Intrusion breccia (known as "eruptive" breccias in Russian literature) occurs as lense-like bodies up to 30 m thick at the top of the Norilsk 1, Norilsk 2, Chernogorka, Talnakh and Mt. Pegmatitovaya intrusions. The intrusion breccias are composed of fragments of basalts and Tunguska argillites, sandstone and coals cemented by magmatic while heavily metasomatized matrix. The Tunguska coal in breccias that are emplaced into trap basalt over 1 km in stratigraphy above the Tunguska source rocks suggests significant lateral transport of the fragments for more than several kilometres.

According to Lyulko et al. (1972), magmatic breccia is represented by a breccia-textured variety of taxitic gabbrodolerite that includes fragments of metamorphosed sedimentary rocks (hornfelses, anhydrite and carbonate marbles) and neighbouring igneous rocks metamorphosed into granular aggregates. Our XRF mapping and chemical data suggest that taxitic gabbrodolerite from both upper and lower marginal series should be considered as a true magmatic breccia where most clasts have been dissolved with a small proportion of semi-dissolved xenoliths present. Some varieties of picritic gabbrodolerite with fragments of granular olivine and clots of chromite likely belong to magmatic breccias as well. Fragments of leucogabbro and anorthosite among gabbrodolerite in the central parts of magmatic conduits also indicate intra-magmatic brecciation of the earliest cumulates and floats. The fragments of leucogabbro are sporadic in the differentiated series of the Norilsk-type ore-bearing intrusions, but plagioclase-rich clasts locally accumulate in thick clast-rich layers in the Morongo-type intrusions. As a whole, the diversity of the fragments indicates a pulsatile character of magmatic influxes with earlier cumulates underwent periodic fragmentation and further separation in the extended (tens of kilometres) plumbing systems.

Frontal breccias are typical for the frontal aureole of the intrusions emplaced into evaporitic-haloic rocks within the Kharaelakh ore field. The igneous body there splits into smaller apophyses (tens of meters) and offshoots (up to half meter) surrounded by peperite-like rocks that are formed by spraying of low-viscosity magma into evaporites with a scale of mingling in the cm scale and smaller. These fluidal dolerite clasts are not, therefore, true fragments but frozen injections of liquid as evidenced by common quenched glass margins. The "peperitic" aureole was formed at a depth of at least 1 km so the ductile regime of brecciation was partly supported by elevated pressure and partly by melt depolymerization due to excess of halogens and other volatiles from evaporite.

Brecciation is typically induced and accompanied by a release of volatiles that were derived from consumption of xenoliths by magma along the pathways. The bulk composition of an intrusion, therefore, cannot be used to infer a parental melt composition because of an undefinable degree of assimilation in the marginal series.

## **Role of hydrogeochemistry in the discovery of the Talnakh-Oktybrysky Cu-Ni-PGE deposit: an historical account**

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The discovery of the Talnakh Cu-Ni-PGE deposits represents one of the greatest mineral discoveries in history and forms the largest ore deposit in the Norilsk-Talnakh camp, Russia. Most of the information on the discovery is in disparate locations and exclusively in Russian.

Discovery histories, even those told in considerable hindsight, can be informative for active explorers, as they provide accounts of the decision making process under the uncertainty of the scientific data that exists at any given time.

In this contribution we pull together a review of the discovery from hundreds of separate reports including interviews with the discoverers. The result is a story telling narrative rather than a scientific account, but it does highlight the use of new technology at different search spaces that lead to the discovery of the supergiant Oktybrysky deposit in 1965. Of particular note is the role of both surface and bore hole hydrogeochemistry, technology that is considered embryonic still today, but played a pivotal role in the discovery of the world's biggest ore deposit 55 years ago. This story forms a nice reminder of the role of trialling techniques especially in deeper search spaces around existing deposits, the so called 'donut of regret'.

## **S/SE RATIO OF SULFIDE ORES AND POTENTIAL CRUSTAL CONTAMINANTS OF THE OKTYABRSK DEPOSIT, NORILSK-TALNAKH ORE DISTRICT**

Marfin, A.E.<sup>1</sup>, Ivanov A.V.<sup>1</sup>, Pashkova G.V.<sup>1</sup>, Brzozowski, M.J.<sup>2</sup>, Radomskaya T.A.<sup>3</sup>, Chubarov, V.M.<sup>3</sup>

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The Oktyabrsk PGE–Cu–Ni deposit is located in the northwest of the Siberian platform and is the largest deposit in the Norilsk–Talnakh ore district. The ore types in the Oktyabrsk deposit comprise disseminated base-metal sulfides (BMSs) in picritic and taxitic gabbrodolerites of the Kharaelakh intrusion, veinlet–disseminated BMSs in Devonian sedimentary rocks above the intrusion, and massive BMSs at the contact zone with Devonian rocks at the base of the intrusion. Several models have been proposed for the formation of the Norilsk–Talnakh PGE–Cu–Ni deposits; the most popular model suggests that the intrusions are open magmatic systems that acted as feeder conduits for the basaltic magmas at the surface.

Based on the heavy S isotope composition of BMSs, this conduit model suggests that sulfur saturation was achieved by the assimilation of anhydrite with isotopically heavy  $\delta^{34}\text{S}$  values (+8‰ to +14‰). The S/Se ratios of chalcopyrite (2,700–5,700) and bulk ores (2,800–8,000), however, are similar to mantle values (2,632–4,350) and notably lower than the S/Se ratio of anhydrite (~200,000). This leads to a paradox – if anhydrite was the contaminant, then why are BMSs characterized by crustal S isotope signatures, but mantle-like S/Se ratios? One possibility is that the S was sourced from some other crustal reservoir other than anhydrite. Other potential reservoirs in the Norilsk region include coal and black shale, which have S/Se ratios of 6,000–15,000 and ~7,000, respectively.

The S/Se ratios of chalcopyrite and bulk ores are more similar to the S/Se ratios of coal and black shale compared to anhydrite. Based solely on S/Se ratios, coal seems to be the more likely contaminant that led to sulfur saturation in the Oktyabrsk deposit. This conclusion differs from the interpretations made using S isotopes, in which anhydrite was suggested to be the main contaminant. Clearly, utilizing S isotopes or S/Se ratios independently is not sufficient to accurately characterize the nature of contamination in this mineralized system. This example illustrates the need to use these geochemical proxies in combination when characterizing the contamination history of Ni–Cu–PGE deposits.

This work was funded by the Ministry of Science and High Education of the Russian Federation No 075-15-2019-1883.

## Origin of zircon from the Noril'sk-type economic intrusions: evidence from morphological, compositional and isotope data

Malitch, K.N.<sup>1</sup>, Belousova, E.<sup>2</sup>, Griffin, W.L.<sup>2</sup>, Martin, L.<sup>3</sup>, Badanina, I.Y.<sup>1</sup> and Sluzhenikin S.F.<sup>4</sup>

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Despite years of research into the world-class Ni-Cu-PGE sulfide deposits related to the Kharaelakh, Talnakh and Noril'sk-1 mafic-ultramafic intrusions within the Noril'sk Province, their origin remains a subject of ongoing debate. Zircon, as an inert mineral, has a unique ability to preserve the isotopic-geochemical signatures of earlier events (U-Pb age, Lu-Hf- and O-isotope systems), recording different stages of rock formation and magma sources. Recent detailed morphological, *in situ* rare earth element (REE) and U-Pb isotope studies of zircon from the economic Kharaelakh, Talnakh and Noril'sk-1 intrusions identified the polyphase nature of zircon and defined multiple age clusters indicative of a prolonged evolution of the magmas parental to economic intrusions in deep-seated chambers, and later recrystallization of the intrusive rocks in the crust (Malitch et al., 2018, and references cited therein).

Zircon has been observed in thin sections as single or polyphase grains enclosed in clinopyroxene, amphibole or mica, frequently intergrown with apatite. Rare examples show overgrowths of zircon on baddeleyite, implying that baddeleyite is likely to be the first mineral to crystallize in this assemblage. Separated zircon grains are represented by idiomorphic and subidiomorphic transparent and semi-transparent light beige, pale crystals that usually do not exceed 125 µm. In the *Pupin* diagram (Pupin, 1980), type D crystals predominate (76 %) among the investigated grains. Zircons are characterized by a fuzzy (smoky) cathodoluminescence and a virtual total absence of zoning. However, observations under the petrographic microscope revealed a polyphase inner structure in the studied grains, which are composed of different (up to four) zircon populations with distinct solid-inclusion assemblages (dominated by minerals and glass, respectively). Zircons have high concentrations of thorium and uranium with Th/U >1, and chondrite-normalised REE patterns typical of igneous zircon (Belousova et al., 2002). In REE discrimination diagrams in (Sm/La)<sub>N</sub> – La and Ce/Ce\* – (Sm/La)<sub>N</sub> spaces, zircons mainly plot in the field of “magmatic” zircon (after Hoskin, 2005).

Hf-isotope data on zircon and baddeleyite, which reflect their source region, show a significant range in initial <sup>176</sup>Hf/<sup>177</sup>Hf values along with a less pronounced range in the initial <sup>143</sup>Nd/<sup>144</sup>Nd values of rocks, which favors a model of mixing between the asthenospheric and lithospheric sources. Following previous studies (Arndt et al., 2003; Malitch et al., 2018), the major set of εNd values around +1.0 in rocks of economic intrusions is attributed to limited crustal contamination, presumably in deep magma chambers, whereas the smaller set of negative εNd values in taxitic-textured rocks is consistent with greater involvement of a crustal component and reflects an interaction with the wall rocks during and probably after the emplacement. This notion is supported by *in situ* oxygen isotope data collected for zircon grains from variously mineralized rocks of the Talnakh intrusion (Malitch et al., 2020). Zircons from gabbrodiorite, gabbroic rocks of the layered series and ultramafic rocks have similar mantle-like mean δ<sup>18</sup>O values (5.39±0.49‰, 5.64±0.48‰ and 5.28±0.34‰, respectively), consistent with a mantle-derived origin for the primary magma(s) parental to the Talnakh intrusion. In contrast, zircon from a sulfide-bearing taxitic-textured troctolite from the basal part of the intrusion has high δ<sup>18</sup>O (mean of 6.50‰), indicating the possible involvement of a crustal component during the formation of sulfide-bearing taxitic-textured rocks. Thus, *in-situ* Hf- and O-isotope compositions of zircon record the evolution of the magma chamber, with input of magmas from different sources, and/or progressive contamination by country rocks. A prolonged period for the concentration of the ore components in deep-seated staging chambers during this interaction might be a key factor in the formation of economic deposits.



## Linking the Siberian flood basalts and Ni-Cu-PGE sulfide deposits at Noril'sk

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The Noril'sk region is the most thoroughly studied region of the Siberian Traps due to the presence within it of world-class magmatic Ni-Cu-PGE deposits. Over the past few decades, however, Western and Russian geologists have come to hold strongly polarized viewpoints on the causal connection between the ore-forming processes and other magmatic processes in the large igneous province (LIP), which make it difficult to draw lessons for exploration in other regions. Here, with the aid of thermodynamic and fluid-dynamic simulations, we provide a comprehensive model of the Noril'sk-type deposits to reconcile the seemingly contradictory viewpoints, and propose that these deposits have a genetic link to the voluminous Siberian Traps that overlie them but do not occupy feeders to the flows.

Equilibrium pressure-temperature estimates for clinopyroxene phenocrysts in the Middle and Upper series of Siberian flood basalts mostly cluster at 1130-1200°C and ~5-15km depth, suggesting that prolonged magma storage occurred within the Later Proterozoic sedimentary suites and upper granitic basement. Based on thermodynamic modelling, the metal-depleted *Nd* basalts and complementary sulfides were produced when mantle-derived *Tk* picritic basalts assimilated granitic gneisses within this deep-seated magma reservoir. Sulfide generated in this first-assimilation stage can strongly scavenge Ni, Cu and PGE, and due to gravitational settling, coalescence and accumulation at lowermost levels of the reservoir they were sequestered at depth. The magma reservoir was subsequently replenished by episodic pulses of basalt along a spectrum of compositions. Early-formed sulfides were partially dissolved and gradually attained increasing metal tenors, and the silicate/sulfide ratio for this upgrading is less than 1000. Meanwhile, a slow infusion of isotopically heavy sulfur derived from assimilation of anhydrites hosted by overlying carbonate strata into the reservoir drove a gradual evolution of the deep sulfide reservoir from mantle-like compositions to relatively uniform heavy isotopic S within 2000-3000 years (until the time of *Mr-Mk* boundary).

Sharp/interfingering boundaries between lithologic stratigraphy of economic intrusions favour magma emplacement in multiple pulses. The main *Gabbrodolerite Series* are crystallized directly from magma resembling *Mr* basalts, containing 1% early-formed olivine, and further cooling of the residual melts expelled from the compacting crystal framework accounts for the overlying *Residual Series*. Ore-bearing picritic gabbrodolerites are the products of in-situ assimilation of sedimentary rocks during late injection of basalt resembling the *Mr-Mk* basalts, laden with olivine+plagioclase phenocrysts and sulfide melts from the staging reservoir. This second assimilation process may also trigger segregation of sulfides, but their contributions are suggested to be local and unimportant. Because our modelling suggests that the ore-forming magma ejected from the deep reservoir are vigorous to suspend and transport up to 10 vol.% of sulfide melts. Within magma reservoir, the overpressure associated with a new injection of *Mr-Mk* basalts has increased to a level sufficient (~20 MPa) for lofting of the sulfide-laden magma. After this magma flow was deflected into sub-horizontal bodies, dense sulfides settled from the main flow of the emulsion, accumulating at low-lying places to form sulfide pools, which has been modelled by the computational fluid dynamics simulation. Here, the mineralized intrusions and associated peripheral sills are self-contained, comagmatic products of the Siberian LIP within shallow sill networks, rather than the feeder conduits for magmas vented at surface.

Establishing this causal connection between the mineralized intrusions and overlying Siberian Traps in Noril'sk region, has great implications for a paradigm shift of "conduit-type" magmatic deposits and exploration in other worldwide LIPs.

## Understanding genetic processes at Norilsk by combining in-situ LA-ICP-MS and S isotopic data on different sulfide textures

Margaux Le Vaillant<sup>1</sup>, Stephen. J. Barnes<sup>1</sup>, Laure A. J. Martin<sup>2</sup>, Noreen J. Evans<sup>3</sup>, Louise Schoneveld<sup>1</sup>, Belinda Godel<sup>1</sup>, Michael Verrall<sup>1</sup>

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This study presents the results of in-situ characterisation of different coexisting sulfide textures present within the globular disseminated ores of the Norilsk Ni-Cu-Co-PGE mineralised intrusions. The aim is to gain a better understanding of the genetic processes at play for these different textures and for the ore bodies as a whole.

Two specific techniques were used: *in-situ* laser ablation ICP-MS, and *in-situ* S isotopic analyses. Both techniques provide information on specific genetic processes: (1) S assimilation and crustal contamination and (2) interaction between the sulfide melt and the silicate melt within the magmatic plumbing system. S isotopic compositions of the sulfides allow interpretations on the potential source of the S, and of re-homogenisation of this S isotopic signature of the sulfides during interaction with the silicate melt. On the other hand, trace element compositions of the main sulfide minerals, especially Pd and Se contents of pentlandites, can be proxies for sulfide melt composition and hence can provide indications of relative variation in the efficiency of sulfide-silicate element partitioning at the scale of individual blebs. These two datasets were also combined with a 3D characterisation of the sulfide textures within representative samples. This 3D characterisation allows the identification of three textural types: large globules, interstitial frameworks connected to globules, and isolated disconnected blebs.

In most cases, sulfides of all textural types within individual samples present similar S isotopic compositions and similar Pd in pentlandite contents, indicative of a common original sulfide melt that experienced different degrees of post-accumulation percolation. However, in one of the samples (VZU3C), for which we used 3D micro CT scans to identify completely isolated sulfide droplets (definitely not interconnected with either the disseminated or the large sulfide blebs), we can observe a slight difference in the Pd in pentlandite and  $\delta^{34}\text{S}$  composition, with the fully isolated droplets being slightly more enriched in Pd and having slightly lighter  $\delta^{34}\text{S}$  values. This would be compatible with a slightly higher R factor: small droplets would be easier to transport within the silicate melt and have a relatively larger specific surface area to exchange with the silicate melt.

There are two clear observations within this dataset. First, the heavy  $\delta^{34}\text{S}$  signature of the sulfides, reflecting the assimilation by the melt of large amounts of heavy crustal S, with values that are homogeneous within each sample, but vary widely between intrusions (varying between 4.7 ‰ and 17 ‰  $\delta^{34}\text{S}$ ), and even between samples from the same intrusion (12‰ to 17‰  $\delta^{34}\text{S}$  in samples from the Kharaelakh intrusion). Secondly, the pentlandite is enriched in Pd, a result of high R factors coupled with the magmatic-peritectic origin of much of the pentlandite. However, one of the interesting and puzzling observations within this dataset is the lack of correlation between the increase in Pd contents in pentlandite and the decrease in  $\delta^{34}\text{S}$  compositions as would be expected if; 1) increase in Pd tenors is due to an increased R factor (silicate/sulfide liquid mass ratio), and 2) diffusion of Pd and of the various S isotopes between the silicate melt and the liquid sulfide droplets occurs at a similar rate. This might suggest that there are other factors at play, such as contrasting diffusivities for Pd and S, or S isotopic fractionation during interaction with a volatile phase.

## **The role of magma degassing in sulphide melt mobility and metal enrichment**

Iacono-Marziano G.<sup>1</sup>, Le Vaillant M.<sup>2</sup>, Barnes S.J.<sup>2</sup>, Godel B.<sup>2</sup> and Arbaret L.<sup>1</sup>

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A strong association between sulfide droplets and gas bubbles has been observed in both experimental and natural samples (e.g. the picrogabbrodolerites of the Norilsk-Talnakh ore-bearing intrusions), suggesting that the fluid phase may have a major control on the segregation and mobility of the sulfide melt. Here we show how the association between sulfide melt and gas bubbles during magma degassing can have consequences for the accumulation of the sulfide liquid but also for its metal enrichment. Two types of experiments are presented involving magma degassing in sulfide-bearing mafic magmas at 1200°C and variable pressure: experiments simulating the interaction of the magma with coal, and experiments simulating magma decompression. Despite a marked difference in the composition of the fluid phase of the two types of experiments, the sulfide melt and the fluid phase are always associated, with each gas bubble being generally connected to one or several sulfide droplets. By facilitating the coalesce of the sulfide droplets attached to the same gas bubble, the fluid phase therefore seems to play a crucial role on the accumulation of the sulfide liquid. Large sulfide blebs are produced by this process in experimental samples, suggesting that magma degassing can be a potentially critical mechanism for sulfide mobility and accumulation in magmas.

Moreover, magma degassing can also play a role on metal content of the sulfide melt: metal enrichment of the sulfide droplets is observed in the degassed samples, due to the consumption of the sulfide melt consequent upon magma degassing. In experimental samples, limited degassing produces metal-enriched sulfide melts, while extensive degassing generates PGMs. The possible implication of this process in the formation of ore-deposits and particularly in those of Norilsk-Talnakh is discussed, with a particular attention to the disseminated sulfides in the picrogabbrodolerites and the S-poor, PGE-rich ores.

## **A proposed genetic link between Proterozoic magmatism and metallogenesis in Australia and the Bushveld superplume**

Fiorentini M. L.<sup>1</sup>, O'Neill C.<sup>2</sup>, Giuliani A.<sup>3,4</sup>, Choi E.<sup>1</sup>, Maas R.<sup>4</sup>, Pirajno F.<sup>1</sup>, Foley S.<sup>2</sup>

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The convective processes responsible for the dispersion of heat from the Earth's core to its outer surface are reflected in the formation of mantle plumes (Morgan, 1971; Richards et al., 1989), which can result in the emplacement of enormous amounts of magma into the crust over very short time spans, generally less than 5 Ma. These large-scale mantle convective processes are commonly reflected in the emplacement of Large Igneous Provinces (LIPs). These are high-volume, short-duration magmatic events consisting mainly of extensive flood basalts and their associated plumbing systems.

During the evolution of our planet from the Archean to the present, the size and magnitude of mantle plumes has varied greatly, reflecting both secular cooling and the cyclic assembly and breakup of supercontinents. Geological evidence shows that deep mantle plume activity and associated high-volume magmatism have strong impacts on the continental crust and the Earth's surface, e.g. through their role in continental break-up, formation of large ore deposits and as drivers of dramatic environmental change.

One of the most voluminous LIPs in the geological record is the ~2.06 billion-year-old Bushveld Igneous Complex of South Africa (BIC), which hosts the largest known reserves of platinum group elements (PGEs), vanadium and chromium on Earth. However, syn-BIC magmatism appears to be limited to the Molopo Farms Complex and to a few satellite intrusions in southern Africa within a radius of <500 km from the BIC. The apparent lack of a spatially extensive magmatic footprint appropriate to the inferred large size of this LIP is surprising and possibly related to dispersal of part of the syn-Bushveld magmatic record through plate tectonic activity.

To test this hypothesis, here we present new radiometric ages for alkaline magmatism in the Archean Yilgarn Craton of Western Australia, which overlap the emplacement age of the BIC and indicate a much more extensive geographic footprint of the BIC magmatic event. To assess plume involvement at this distance, we present numerical simulations of mantle plume impingement at the base of the lithosphere, and constrain a relationship between the radial extent of volcanism vs time, excess temperature and plume size. These simulations suggest that the thermal influence of large plume events could extend for thousands of km within a few million years, and produce widespread alkaline magmatism, crustal extension potentially leading to continental break-up, and large ore deposits in distal sectors. Our results imply that superplumes may produce very extensive and diverse magmatic and metallogenic provinces, which may now be preserved in widely-dispersed continental blocks.

## Up close and personal with the Merensky Reef: insights from $\mu$ XRF and SEM mapping

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The Merensky Reef hosts one of the largest platinum group element (PGE) resources globally. It has been exploited for nearly 100 years, yet its origin remains unresolved. In the present study, we characterised eight samples of the reef at four localities in the western Bushveld Complex using micro-X-ray fluorescence and field emission scanning electron microscopy. Our results indicate that the Merensky Reef formed through a range of diverse processes. Textures exhibited by chromite grains at the base of the reef are consistent with supercooling and *in situ* growth. The local thickening of the Merensky chromitite layers within troughs in the floor rocks is most readily explained by granular flow. Annealing and deformation textures in pyroxenes of the Merensky pegmatoid bear testament to recrystallisation and deformation. The footwall rocks to the reef contain disseminations of PGE rich sulphides as well as olivine grains with peritectic reaction rims along their upper margins suggesting reactive downward flow of silicate and sulphide melts. Olivine-hosted melt inclusions containing Cl-rich apatite, sodic plagioclase, and phlogopite suggest the presence of highly evolved, volatile-rich melts. Pervasive reverse zonation of cumulus plagioclase in the footwall of the reef indicates dissolution or partial melting of plagioclase, possibly triggered by flux of heat, acidic fluids, or hydrous melt. Together, these data suggest that the reef formed through a combination of magmatic, hydrodynamic and hydromagmatic processes.

## **Petrology of the Zvishavane Ultramafic Complex, south-central Zimbabwe, and speculations on why it lacks platinum-group element mineralization**

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The Zvishavane Ultramafic Complex (ZUC) crops out wholly within the 3.5 Ga (Paleoarchean) Zvishavane gneiss complex basement of the Zimbabwean craton onto which the Mberengwa greenstone belt was deposited. ZUC hosts the largest deposit of chrysotile asbestos in Africa. ZUC is world-renowned for its high-grade chrysotile asbestos, as well as the Shabani Mine, Africa's largest asbestos deposit. Despite its huge economic importance, no mineral composition studies have yet been conducted on the ZUC. This study reports on petrographic and mineral composition data from this complex and attempts to place some constraints on the evolution of this body based these data.

The 1500m-thick ZUC covers an area of 15 km long and 2.5 km wide, and strikes in a north-westerly direction, with a dip of 60° to the south. From the base upwards, ZUC is composed of dunites, peridotites, pyroxenites, and gabbros, all metamorphosed to varying degrees. Dunites and peridotites have also largely been serpentinized, although some relict olivine crystals are observed under the petrographic microscope. Pyroxenites and gabbros have also been metamorphosed, with no orthopyroxene observed in the suite of samples investigated. Clinopyroxene, feldspars, and zoned amphiboles were identified in metagabbros. Epidote occurs in association with feldspars in metagabbros. Compositions of olivines range from Fo<sub>90.5-96.8</sub>, pyroxenes are all augites and diopsides (Ca<sub>30.9-56.5</sub>Mg<sub>33.9-47.8</sub>Fe<sub>5.6-22.9</sub>), plagioclases are all Na-rich, with compositions of An<sub>0.06-41.9</sub>, and they plot in the high albite, oligoclase, and andesine fields. The sodic feldspars formed from metamorphism of calcic-rich ones. Zoned amphiboles have cores of magnesio-hornblende and rims of actinolites whereas serpentine plots in the chrysotile and lizardite fields as well as in the antigorite field. Olivines are all enriched in magnesium, with compositions of Fo<sub>90.5-96.8</sub>. Epidotes and all enriched in aluminium, and plot in the clinozoisite field, and formed from feldspars.

The calcic clinopyroxenes documented here are consistent with metamorphic clinopyroxenes, whereas the Mg-rich olivines are consistent with formation from Mg-rich magma inferred to have been prevalent during Archean times. Zoned amphiboles are consistent with a two-stage evolution of the amphiboles, with the cores indicating that the ZUC was subjected to amphibolite facies conditions likely during emplacement of the nearby 2.95 Ga Mashava tonalite, and later affected by greenschist facies conditions which likely during emplacement of the 2.63 Ga Zvishavane granite which was accompanied by faulting of the ZUC. Application of various amphibole-plagioclase pairs yields temperatures and pressures of metamorphism of the ZUC of 480-650°C and 1-5 kbars, respectively; conditions that are consistent with greenschist to amphibolite facies metamorphic conditions, and contact metamorphism. These temperatures and pressures support the involvement of fluids, inferred to be associated with the intrusion of granitic plutons, in the formation of the chrysotile asbestos deposits at ZUC.

The predominance of metaperidotites, which comprise 90% of the ZUC lithologies, in comparison to only 10% for metagabbroic rocks, suggests an origin for the ZUC as an ultramafic sill that is comparable in terms of age, lithology, and host rocks to other ultramafic sills elsewhere on the Zimbabwe and Kaapvaal cratons. ZUC, and possibly other similar sills, lack platinum-group element (PGE) mineralization as any PGE-enriched horizons that may have been formed were most likely to have been mobilized and redistributed by later processes such as metamorphism and fluids associated with intrusion of granitic plutons. Additionally, the possible absence of sedimentary crustal materials incorporated by ZUC parental magma may also have deprived the ZUC of any externally derived sulfur that may have helped to trigger precipitation of sulfides and associated PGEs.

## **Chromite Mineralization and Igneous Stratigraphy of the Blackbird Deposit, Ring of Fire, Ontario, Canada**

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The Double Eagle intrusion is one of a series of mafic-ultramafic intrusions of the circa 2.73 Ga Esker Intrusive complex in the McFaulds Lake greenstone belt that hosts chromite mineralization and forms part of the Ring of Fire (RoF) Intrusive Suite. Located in the James Bay Lowlands of Northern Ontario the RoF region has been the focus of mineral exploration since the early 2000s culminating in the delineation of the Eagle's Nest Ni-Cu-(PGE) magmatic sulfide deposit, and a series of chromite deposits including Blackbird.

The Double Eagle intrusion which hosts the Blackbird Cr deposit, was emplaced near the stratigraphic base of the greenstone belt, at the contact with 2773 Ma tonalite-granodiorite in the footwall and 2782 Ma supracrustal rocks in the structural hanging wall. While not yet dated, it is believed to be coeval with the 2734 Ma Black Thor intrusion located 7km to the northeast based on several geological similarities.

The Double Eagle intrusion is cut by the northeast trending Frank Shear Zone (also referred to as the Triple-J fault) resulting in ~1.2km of dextral displacement and division of the intrusion into the northern AT1 segment, and the southern Blackbird segment. When re-constructed, the Double Eagle intrusion appears to form a transitional dike/chonolith form with a pointed base defined by the AT1 feeder dyke and a wider crudely layered top defined by the Blackbird intrusion. This paper focusses on the geology of the Blackbird intrusion which hosts the Blackbird chromite deposit.

Within the Blackbird intrusion, there is an estimated 950m of igneous stratigraphy preserved. This has been broadly divided into the Lower, Middle and Upper Series. The Lower Series (~360m thick) forms the basal portion of the Blackbird intrusion and is dominated by olivine cumulates containing eutectic chromite. The Middle Series (~400m thick) is defined by the onset of excess chromite accumulation. Lithologically the rocks are dominated by lherzolite with cumulus olivine, significant orthopyroxene component, and ubiquitous chromite. Intercalated within the Middle Series stratigraphy is harzburgite and locally thick but discontinuous chromitite layers. Chromite accumulation is generally stratabound and varies from disseminated to thin intercalated layers to thick accumulations of massive chromitite lenses as defined by the BB2-1 lens. The BB2-1 chromitite lens, and the stratigraphically equivalent BB2-4 lens, are the thickest accumulations of chromite in the intrusion averaging ~20m true thickness (at 35-40 % Cr<sub>2</sub>O<sub>3</sub>) of massive chromitite with strike and dip dimensions exceeding 700m. These two lenses comprise >85% of the Measured and Indicated chromite resource calculated by Micon in 2010 and are the focus of initial chromite development plans by Noront in the Ring of Fire.

The BB2-1 and BB2-4 lenses define the top of the Middle Series and the highest stratigraphic interval of chromite accumulation. Overlying the BB2-1 chromitite lens is the Upper Series (~225m thick) which displays a sharp basal contact of pyroxenite and lesser harzburgite with decreasing olivine content up stratigraphy. Pyroxenite of the Upper Series fractionates up stratigraphy to melagabbro and gabbro. The onset of feldspar crystallization within the igneous stratigraphy of the Upper Series coincides with the occurrence of stratabound PGE enriched horizons that can contain up to 1 g/t Pt+Pd over 19 m. The upper contact of the intrusion appears sharp but is partially obscured by late intermediate intrusions emplaced along the contact between gabbroic rocks of the Upper Series and overlying supracrustal rocks.

## **Unravelling sill emplacement using 3D seismic reflection data: implications for mineralisation**

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Many ore deposits are associated with igneous sheet intrusions, particularly sills and sill-complexes. Improving the efficiency of exploration and extraction of these sill-related ore deposits involves on understanding: (i) the magma source and host rock lithology, which influence the type of ore deposits potentially generated; (ii) how the architecture and emplacement of these plumbing systems may control ore accumulation both within the magma and the adjacent host rock; and (iii) internal magma dynamics (e.g., flow patterns) and its effect on the distribution of heat and magma-hosted ore bodies. Exposure of sills and sill-complexes at the surface have allowed us to examine these systems at a variety of scales, e.g., from large-scale analyses of intrusion geometry and host rock deformation to small-scale mapping of crystal alignments, and have driven our understanding of sill emplacement mechanics. However, the pseudo-2D nature of Earth's surface means it is difficult to visualise and study the 3D geometry of entire sills or sill-complexes, which compromises our ability to constrain magma sources, plumbing system architecture, or regional magma transport processes. Physical and numerical modelling can be used to explore sill and sill-complex emplacement, coupled with host rock deformation and fluid flow, in 3D but without access to natural examples these models cannot easily be tested. Synthesising data and building 3D models from multiple boreholes that intersect sills or sill-complexes uniquely provides the best direct access to the architecture, as well as the small-scale structure, of these magma plumbing systems. Yet these borehole data are still limited in their lateral and vertical coverage.

Seismic reflection data provide 'ultrasound-like' images of Earth's subsurface, allowing us to resolve geological features at the metre-to-decametre scale across vast areas; these data have arguably revolutionized our understanding of numerous Earth Science disciplines. Although primarily used in hydrocarbon exploration, there are various examples where seismic reflection data have successfully enhanced the exploration and extraction of ore-deposits, including those related to magmatism. Despite the power of seismic reflection data to provide 3D images of Earth's subsurface in unprecedented detail, its use as a tool to understand magma plumbing system construction and evolution remains limited. Here we discuss how seismic reflection data can be used to investigate: (i) emplacement of individual sills, particularly focusing on how intrusions are accommodated and interpretation of internal magma flow dynamics; (ii) the role of faults in facilitating magma ascent; and (iii) construction of entire sill-complexes. Throughout the presentation, we will discuss how our findings can be applied to mineral exploration and extraction. Overall, our aim is to promote the use of seismic reflection data as a tool for understanding magma plumbing systems, and associated ore deposits.



## Geometry and emplacement of elongate, finger-like intrusions

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Mantle-derived mafic and ultramafic magma is often portrayed to move through the Earth's crust via networks of sub-horizontal and sub-vertical sheet intrusions (i.e., sills, dykes). Ni-Cu-PGE sulphide mineralisation within these large magma plumbing systems occurs in high-flux channels in a variety of host-intrusion geometries including channelised sills (e.g., Noril'sk), tube-like chonoliths (e.g., Nebo-Babel), blade-shaped dykes (e.g., Expo-Ungava), and dyke-sill transitions (e.g., Eagle). Within these intrusions, economic concentrations of metal sulphides often have pipe-like geometries and in some instances, the host magmatic body is also tube-like, suggesting that magma-flow processes are an important factor for trapping sulphide liquids. However, mineralised magma conduits are only very minor parts of larger magma networks and are rarely exposed at the surface, making our understanding of these structures both an ongoing challenge and a limiting factor in our ability to explore for them. We present results of a field study focussing on the emplacement of elongate magma fingers that may be analogous to mineralised tube-like chonoliths. These magma fingers emerged from the margin of the Paleogene Shonkin Sag laccolith, Montana, USA. The aim of this study was to quantify magma finger geometries and to assess how host-rocks (Cretaceous Eagle Sandstone) deform to accommodate their emplacement. We then compare the geometries of magma fingers observed in the field with larger scale intrusions mapped in three-dimensional (3D) seismic reflection data located on the NW Shelf of Australia. 3D seismic reflection data can be used to map intrusion morphologies in 3D down to metre scale, and to interpret and map potential magma flow pathways. However, since we cannot use seismic reflection data to characterise intrusion-induced host-rock deformation on a smaller scale, it is important to link seismic interpretation with field observations, together with the predictions of numerical and analogue models to better understand the emplacement of finger-like intrusions.

Previous studies suggest that magma fingers may form due to elastic or viscous instabilities at propagating sill fronts and that their emplacement is accommodated by either 1) mode I failure, 2) mode II failure, or 3) host-rock fluidisation. However, our field observations show that the emplacement of magma fingers at the margin of the Shonkin Sag laccolith was accommodated by a combination of all three proposed end-member mechanisms. Evidence for host-rock fluidisation is mainly observed at the cross-sectional, lateral tips of the fingers. Shear failure, thrusting, buckling, and folding is observed between laterally adjacent magma fingers, while uplift of strata only makes a minor contribution to accommodating magma finger emplacement. We often observe all three deformation mechanisms in the same outcrop at metre scale, and in some cases associated with a single magma finger. Preliminary photogrammetric analyses suggest that magma fingers related to host-rock fluidisation have rounded to parabolic lateral tip geometries in vertical cross sections oriented perpendicular to the long axis of the magma finger, whereas fingers associated with brittle and/or ductile deformation have blunt to rectangular cross-sectional tip geometries. Thickness-width aspect ratios are in the range of 0.05–0.65, in agreement with measurements from larger, finger-like intrusions observed in 3D seismic reflection data. The observed metre-scale spatial variation in host-rock deformation mechanisms indicates that magma finger emplacement is likely to be accommodated by multiple deformation mechanisms. We conclude that host-rock fluidisation in combination with brittle and ductile deformation accommodated magma emplacement at the margins of the Shonkin Sag laccolith. We further hypothesise that deformation mechanisms may influence magma finger geometries and, based on 3D seismic reflection data interpretation, that magma fingers first grow in width before vertical inflation dominates their emplacement.

## **The effect of solidification on formation and propagation of finger-like conduits: An experimental approach with application to sulphide deposits**

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Solidification effects may play an important role in controlling the geometry of igneous intrusions, including channelized magma feeders, which often trap economic concentrations of Ni-Cu sulphide ores. Here, we use a series of scaled laboratory experiments to investigate the role of solidification on the propagation and morphology of sill intrusions. Hot coconut oil (magma analogue), that solidifies during its emplacement, is injected as a sill into layered colder Laponite RD gel (visco-elasto-plastic host rock analogue). The volumetric injection rate and temperature are maintained constant during each experiment and are systematically varied between experiments. Sill intrusions with less pronounced solidification effects (high injection temperature) show the development of finger-like segments that exhibit an internal branching pattern with patchy solidified areas before the analogue magma erupts at the surface. These morphologies are similar to those observed in isothermal experiments. Conversely, when solidification effects are pronounced (low injection temperature), sill intrusions develop planar outer margins without internal branching and display lobes and time dependant, internal meandering channels that connect the central feeder to the lobes. These sills are discontinuous and develop discrete lobes, representing periods of momentary tip arrest during sill propagation. Since the injection rate is constant, these different behaviours are due to thermal and solidification effects within the intruding magma analogue. Solidification is observed at the top and the bottom of intrusions, while their interiors remain partially solidified and channelized. For a constant injection rate, when the solidification effect is increased, the intrusion area decreases, while both its thickness and the number of discrete lobes increases. Previous literature using solidifying magma analogues and visco-elastic gelatine host materials show similar discrete lobe-like morphologies during solidification, but the long, narrow, channelized feeders and internal flow patterns seen in our experiments were not observed. The complex, non-planar propagating sill margins and internal magma channelization observed in our experiments are similar to shallow magmatic intrusions in nature and finger-like conduits associated with magmatic sulphide deposits. This suggests that magma solidification, together with host rock rheology, play major roles in determining the modes of magma propagation, internal flow morphologies, and possibly the distribution of sulphide mineralisation in sill intrusions.

## **On the origin of a late gabbroic unit associated with the Eagle East ultramafic intrusion in Marquette County, Michigan, USA**

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Exploratory studies have identified a sub-vertical plug-like gabbroic intrusion near the base of the Eagle East ultramafic intrusion in the Upper Peninsula of Michigan. U-Pb baddeleyite dating of this gabbro yields an age of  $1103.4 \pm 1.2$  Ma, suggesting an origin during the early stages of magmatism associated with the Midcontinent Rift System (MRS). Drill core observations indicate that this gabbroic intrusion cuts across the eastern-most portion of the conduit of the Eagle East ultramafic intrusion. The interior portion of this gabbroic unit is sulfide-poor, and it is primarily composed of two rock types: gabbro and gabbro norite, which collectively consist of 50 to 60% plagioclase, 15 to 25% clinopyroxene, 0 to 15% orthopyroxene and 0 to 5% olivine. In the peripheral parts of this intrusion there is a 3-5-meter sleeve composed of gabbro and feldspathic pyroxenite which contains minor blebs of chalcopyrite and pyrrhotite. In addition, a small peridotite pocket has been identified within the main gabbroic unit of the intrusion which contains significant quantities of sulfide minerals with massive and semi-massive textures.

The overall petrological characteristics and the modes of occurrence of sulfide minerals in the small peridotite pocket is similar to the larger Eagle and Eagle East intrusions nearby. Composition of olivine in the main gabbroic rock lies in the range: Fo<sub>24-30</sub>, but olivine from the internal peridotitic unit show compositions around Fo<sub>74</sub>. The Ni-concentration in the olivine of the host gabbroic unit is below 100 ppm, whereas in the Mg-rich olivine of the peridotite is between 2100 and 2800 ppm.  $\delta^{34}\text{S}$  values of sulfide minerals in the outer edges of the main gabbroic unit and in the peridotite pocket encompass a range between -0.6 and 7.0‰ with most values slightly higher than 2‰.

MELTS modelling shows that the origin of the gabbro unit could be explained by the crystallization of a fractionated late derivative of an original high-MgO picritic magma which has been proposed to be the parental magma of Eagle and Eagle East intrusions. The peridotite pocket is a xenolithic representative of these larger intrusions which was captured and entrained by this late magmatic pulse.

## Role of compound drops in magmas

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Natural magmas commonly include at least three mutually immiscible fluid phases, namely, sulfide melt, vapour, and silicate melt. It is also possible for brine and/or carbonic fluid and a second metal-rich liquid, e.g., bismuthide or arsenide, to exist with these three. Experimental, petrographic, and field evidence all show that over a wide range of conditions, which depend on the ratios of surface tensions along two-phase boundaries among three immiscible fluid phases, globules of vapour and sulfide melt suspended within the silicate melt will join together to form compound drops. The bulk density of a compound drop depends on the densities and volume proportions of the two phases, and it will always be less than that of the dense phase if it occurs alone. As a result, the tendency for dense sulfide liquid to settle out of magmas must in many cases be diminished or completely suppressed, permitting flotation of sulfide melt in buoyant compound drops. The ramifications of this behaviour are potentially immensely important for ore genesis, since sulfide melt is a key agent in the transport and deposition of deposits of Ni, Cu, Au, and the platinum-group elements.

However, the concept should not be applied uncritically. Two important factors may act to mitigate or eliminate the possibility of flotation of sulfide melt and they must be considered whenever appeals are made to sulfide flotation in petrogenetic models. First, not all magmas contain enough vapour to float the amount of sulfide present. Because of the strong dependence of vapour solubility on pressure, coupled with the very large compressibility of vapour, compound drops will tend to form and achieve positive buoyancy only in the upper crust, with some possible exceptions for exceptionally CO<sub>2</sub>-rich magmas at greater depths. Second, the mobility of vapour with or without attached pendant sulfide droplets is hindered by capillary forces in the presence of a mushy framework of silicate minerals. The stranding of compound drops due to capillary forces can only be overcome if the vapour phase is supplied in excess from beneath (i.e., parging) or if there is a strong upward flow of interstitial silicate melt due to compaction or filter pressing. A review of recent published applications of the concept of compound drop transport shows that, to date, there is scant support for its operation in mushy magmatic systems underlying porphyry deposits, whereas it is undoubtedly operative to some extent in mafic-ultramafic systems that form magmatic sulfide deposits including komatiite-hosted (e.g., Black Swan, Raglan) and at Norilsk.

Recent work documents occurrences of rare immiscible metal-semimetal melts (e.g., telluride, arsenide, bismuthide, stannide, antimonide; TABS) forming compound drops with sulfide melt hosted by silicate melts, with ramifications for ore formation. However, the solubilities of TABS in the coexisting sulfide melts are generally very high, whereas the natural abundances of TABS elements are very low. As a result, in almost any imaginable natural circumstance where silicate melt exists in sufficient quantity to transport them, the TABS will be fully dissolved within the sulfide melt rather than occurring as distinct immiscible phases. The principal exception to this rule is expected to occur where sulfide melt has been depleted to extreme degrees either by fractional melting in the upper mantle or by crystallization in the crust; in both instances the volume fraction of silicate melt in the whole system will be very small, so that both the sulfide melt and the TABS melts will be trapped in pore spaces among silicate solids and incapable of physical transport away from their place of formation.

## **Potential origin(s) for garnet growth at silicate-sulphide contacts at Nova-Bollinger**

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The Nova-Bollinger Ni-Cu sulphide ore deposits and their host rocks (Fraser Zone, WA) are characterised by the ubiquitous occurrence of garnet in all types of lithologies: metasediments and metamafics forming the granulite-facies host rocks of the ore bodies as well as massive sulphides. Garnet is commonly used by petrologist as a recorder of metamorphic processes: its major element composition converts to PT conditions whereas its trace element and isotopic compositions (O) can be used to characterise its geochemical environment. The aim of this work is to decipher whether garnet can also be used to record ore-forming processes in the specific context of Nova-Bollinger. We use a multi-method approach to characterise and understand their complex 2D and 3D textural relationships with the sulphides and their chemistry.

This presentation will focus on those garnet crystals growing at the interface between sulphides and silicate-rich rocks. They are widespread regardless the protolith of the silicate-rich rock and display very variable textures including: skeletal crystals with size ranging from <100µm to several cm depending on the samples, dense corona of crystal aggregates or large euhedral garnet crystals mm in size. One sample showing large skeletal garnet growth at the contact between a mafic granulite and massive sulphides has been investigated using micro-CT, Tornado and Maia X-ray mapper. The skeletal garnet shows an evolution in texture and chemistry from the massive sulphide, where it is Cr and inclusion-rich, to the granulite host, where garnet show euhedral crystal shape and oscillatory zoning for Y. In contrast, the massive sulphides show a rugged surface at the contact and many small sulphide inclusions are widespread close to the contact within the granulite. Different hypotheses for the formation of this peculiar texture will be discussed as well as their potential implications for the processes involved in silicate-sulphide melts interactions.

## **Chalcophile trace element indicators of sediment contamination at Muremera-Rujungu (Burundi) and Kabanga (Tanzania)**

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The Muremera and Rujungu (Burundi) and Kabanga (Tanzania) mafic-ultramafic bodies are small, irregular tubular Ni-Cu sulfide-bearing chonoliths emplaced horizontally into a sequence of graphite and/or sulphide-bearing siltstones and mudstones. The mineralized chonoliths are flanked by much more extensive, thin, differentiated sills. The sedimentary and intrusive rocks have subsequently been folded into tight upright folds. A particular problem during exploration is to distinguish between higher grade, medium tenor mineralized intrusions and the more common low grade, low tenor intrusions. We report an investigation of the chalcophile metal content of the extensive sill complexes to resolve this problem.

The sills can be difficult to recognize at surface due to deep weathering and laterite cover, but careful mapping and observation in the Muremera-Rujungu area has allowed us to trace individual sills over at least 1 km along strike. They are better exposed in drillcores, where their internal structure is more apparent and where fresh rock can be sampled. Most sills in the stratigraphic package in which mineralized chonoliths occur vary in thickness from less than 1 m to about 10 m, but thicker sills up to 50 or 100 m occur higher up in the stratigraphy. Almost all thin sills are differentiated into plagioclase-rich upper portions and mafic lower portions (with S-shaped geochemical profiles), though a few sills may be dominated by mafic-rich material (D-shaped profiles). Where well-preserved, the sills have recognizable chilled margins and the adjacent sediments are thermally metamorphosed at both top and bottom margins. Both the sills and the hornfelsed sediments have been affected by a greenschist facies retrogressive overprint, sometimes accompanied by layer-parallel shearing.

The sills have lithophile element compositions like the marginal rocks of the chonoliths (MgO 8 to 13 %; LILE-enriched; Nb-Ta depleted). As such, they appear to represent products of a sediment-contaminated high-MgO basaltic/picritic magma. In contrast to the marginal rocks of the chonoliths, which are often sulphide-rich, the sills are relatively sulphur-poor (< 1 % sulphide). In general, the sill margins have higher S content than the interior, and the upper more felsic part contains more sulphide than the lower mafic division. Some of the common and trace chalcophile elements (Cu, Ag, Bi, Pb, Sn, Te) seem to follow the pattern of S in being enriched at the margins and upper division relative to the inner and lower division. Some of this S (and Cu, Ag, Pb, Sn) may be due to localized remobilization from adjacent sediments. However, Ni and to a lesser extent Co, Pt and Pd do not correlate well with S within the sills. This is partly due to their compatible nature in mafic minerals and indeed, both Ni and Co are usually enriched in the lower mafic division of each sill. However, plots of ratios such as Ni/Cr and Ni/Mg indicate that certain samples of the lower mafic division (usually the most Mg and Cr rich) contain anomalously high Ni. These same samples are usually enriched in As and sometimes Sb (up to 200 ppm and 16 ppm respectively) but are relatively depleted in S and other chalcophile elements.

We propose that the sporadic enrichments of Ni, As and Sb in the lower cumulate portion of the sills represent relics of an immiscible As-rich melt that was derived by assimilation of black shales lower down in the stratigraphy. These black shales (now graphitic andalusite schists) are enriched in As and Sb, in contrast to the sulphide-rich (but not graphitic) sediments that enclose the sills and chonoliths. We propose that higher tenor mineralization is related to earlier (and deeper) sulphide saturation of picritic melts assimilating the As-rich black shales, whereas lower tenor mineralization is associated with bulk assimilation of the upper S-rich sediments.

## Unravelling the crystallisation of Ni-Cu-PGE sulfide at Munali: evidence for Cu migration?

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The Munali Ni-Cu-PGE deposit is a highly complex Neoproterozoic mafic-ultramafic hosted sulfide system situated within the Zambezi Belt in southern Zambia. Located along a regional fault zone, the Munali complex comprises a multiphase composite system with an unmineralised gabbroic core, surrounded by a later marginal mafic-ultramafic breccia unit that is host to the sulfide ore. Yet, Munali displays many atypical features that question the applicability for the genesis of the deposit against traditional models. Munali comprises a suite of geochemically diverse mafic ultramafic host rocks that include gabbro, dolerite and Cr-poor, apatite-bearing dunite, wehrlite and rare clinopyroxenite. Sulfide mineralisation is characterised by sulfide with unusually high Ni/Cu ratios, comprised of pyrrhotite and pentlandite with variable chalcopyrite and pyrite associated with abundant carbonate-apatite-magnetite gangue.

Sulfide mineralisation is predominately present as massive to semi-massive sulfide hosted within sulfide sheets aligned parallel to the orebody that is host to more than 90% of the ore, the remainder comprising disseminated sulfide that is constrained to the marginal intrusive rocks of the complex (gabbro and apatite-magnetite bearing dunite, clinopyroxenite and wehrlite) and footwall carbonate-sulfide veins. Notably, intercumulus and net-textured sulfide are absent, except for secondary pseudo-interstitial textures in ultramafic rocks, the product of sulfide infiltration.

Sulfide shows characteristic magmatic sulfide textures, predominantly as coarse pentlandite cellular loops with high Pd contents (>10 ppm) formed via magmatic-peritectic reaction, which support a high-temperature magmatic origin. Platinum group minerals are nearly exclusively dominated by Pd>Pt tellurides predominantly of the moncheite-merenskyite series. Yet, sulfide geochemistry highlights extremely variable Ni/Cu ratios between 0.5 and 72, alongside moderate to high Pd/Ir<sub>N</sub> ratios (~1690) and an extreme negative Au anomaly. As such, Munali represents a magmatic system that is depleted in Cu and Au in relation to comparable deposits of similar settings and scales.

The orebody displays variable sulfide breccia textures and evidence of post-emplacement deformation and hydrothermal alteration, resulting in chalcopyrite mobilisation on a micro scale. Recognition of a highly fractionated sulfide system on a macro scale may simply represent the inherent characteristics of the parental sulfide composition, with the results of sulfide fractionation retaining the monosulfide solid solution (mss) cumulate portion upon cooling, alongside mobilisation of a residual Cu-rich sulfide liquid. Although sulfide is most closely associated with ultramafic rocks as sulfide sheets, it appears to not be synchronous with ultramafic emplacement with instead later infiltration and brecciation of massive sulfide and the ultramafics representing a 'surrogate' host. The implication of sulfide representing a significantly later fractionated phase suggests that the sulfide may be sourced and/or mobilised from a younger magmatic event and subsequently emplaced within the Munali Complex, and that Cu and Ni orebodies may be separated on a deposit scale.

## **Complex effects of assimilation to sulphide saturation in the Duluth Complex, Minnesota, revealed by modeling with Magma Chamber Simulator**

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Assimilation of sulphurous wall rocks, such as black shales, enhances the potential for a magma to reach sulphide saturation. The effect of assimilation is not confined to the mere addition of sulphur to the magma, but the required sulphur content to reach sulphide saturation (SCSS) can be affected by the changing composition of the magma. The lack of thermodynamically constrained assimilation–fractional crystallization (AFC) models that track the evolution of phase equilibria and their geochemical consequences has hampered the in-depth characterization of this phenomenon.

Selective assimilation is a complicated process that requires the phase equilibria of the partially melting wall-rock to be taken into account. The Magma Chamber Simulator (MCS) is the first software to do this by applying the thermodynamic engine of the MELTS software simultaneously to the magma and the wall-rock subsystems. Furthermore, the MCS can utilize the phase equilibrium data to model the trace element evolution for both subsystems.

We used the MCS software to produce a set of thermodynamically constrained FC and AFC models for a parental magma proposed for the mineralized Duluth Complex rocks. Bulk and selective AFC models were performed with the Virginia Formation black shale as the wall-rock, as it has been identified as the major source for sulphur in the mineralizations. The major element data of the models allowed us constrain the SCSS evolution of the melt. As sulphide phase equilibrium is not included in the thermodynamic database of the MELTS, the sulphur mass balance between the magma and the black shale wall-rock was tentatively modelled using the MCS trace element protocol.

The FC models show that the Duluth Complex parental magmas must have been hydrous ( $\geq 1$  wt.% H<sub>2</sub>O) in order to produce the ubiquitous troctolitic (*sensu lato*) cumulates of the mineralized intrusions. The AFC models reveal that ~20–30 wt.% assimilation is required to crystallize norites instead. This is in agreement with isotopic data from the norites that are observed adjacent to the black shale wall-rocks and xenoliths in the Duluth Complex. Formation of the noritic cumulates affects the liquid line of descent of the magma, e.g., by decreasing the activity of FeO<sup>melt</sup>, and effectively lowers the SCSS of the melt. The mass of the melt phase, however, increases during assimilation, thus lowering the sulphur concentration of the melt, if sulphur is not assimilated from the wall-rock simultaneously. The coupled effects of compositional changes and increasing melt mass to sulphide saturation are significant and intrinsic to AFC systems.

Our preliminary sulphur assimilation models show that both the bulk and selective assimilation scenarios can supply the magma with > 80 % sulphur derived from black shale, which is concordant to the sulphur isotopic composition of the norite-hosted mineralizations. The selective assimilation is preferred as it prefers noritic cumulates over gabbros. The troctolite-hosted mineralizations, however, require either bulk assimilation of anomalously sulphur-rich black shale or effective sulphur mobilization and transportation to the magma during selective assimilation.



## **Caught in the moment: CO<sub>2</sub>-rich fluid exsolution from magmatic sulfides in the middle crust**

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In orthomagmatic systems emplaced at various crustal depths there appears to be a near-ubiquitous paragenetic association of base metal sulfides and platinum group minerals (PGM) with magmatic volatile-rich phases, such as mica, amphibole and carbonate. This observation recently led to the hypothesis that in ascending mantle-derived magmas, volatiles could play a key role in the physical transportation and concentration of dense metal-rich phases across the lithosphere. Whereas in upper crustal mineralised systems (<10 km) the volatile species appears to be dominated by water, it was proposed that in deeper systems (>20 km) a buoyant supercritical CO<sub>2</sub>-rich fluid could stick to dense metal-rich sulfide liquids and PGM and aid their transport upwards. There is currently a knowledge gap as to what is the dominant volatile in the middle crust (10-20 km) and what is the transport mechanism for the metal-rich phases in ascending magmas at this depth interval.

There is a complex relationship between pressure and the solubilities of H<sub>2</sub>O, CO<sub>2</sub> and sulfide in silicate liquids. Depending on the composition of the volatile phase, decoupling between sulfides and volatiles should occur in the middle crust. It is unclear whether this process should either favour the physical concentration of metal-rich sulfides and PGM at that specific crustal depth, or alternatively prime any ascending magmas in metals that could be subsequently concentrated in upper crustal hydrothermal systems. The two scenarios may not be mutually exclusive.

The middle crustal Rudnyi intrusion in the Tsagaan-Shuvuut ridge of NW Mongolia may offer insights into these poorly constrained processes. This intrusion contains sulfide mineralisation in the form of disseminated sulfide globules of various size and shape. Some of the quenched blebs, which display dendritic textures and are interpreted as frozen upon emplacement, are ubiquitously associated with carbonate phases (mainly calcite), displaying clear immiscibility textures. Results from laser ablation ICP-MS on the quenched sulfide blebs show anomalous enrichments in Au and Pt. The larger sulfide globules that escaped quenching do not show any association with carbonate, implying that at the moment of their crystallisation the CO<sub>2</sub> fluid may have already been degassed. It is proposed that the exsolution of the CO<sub>2</sub> fluid from the sulfide liquid could potentially trigger the immiscibility of nanoparticles enriched in precious metals, which could be physically entrained together with the sulfides.

## **Sulfide evolution of the Moran komatiite-hosted Ni deposit, Kambalda, Western Australia**

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The Moran komatiite-hosted Ni sulfide deposit is one of the best preserved orebodies at Kambalda (Western Australia), the type-locality of type 1 komatiite-hosted deposits. Despite upper greenschist metamorphic overprint, igneous textures (undulating basal contacts with sulfide-filled micro-fractures and ferrichromite layers, basalt-sulfide breccia-emulsions on basal contacts, basalt plumes on basal contacts, basalt-sulfide emulsions on basal and upper pinchout contacts, cm-scale silicate-sulfide layering on upper pinchout contacts and a floating vesicular basalt “scum layer” on upper pinchout contacts) are found close to the sulfide-silicate contacts.

The oldest ore-sulfides are found on the flank of Moran and overly older sediments. There is a hiatus between the flank sulfides (representing an early concave embayment in the komatiite lava flow) and the main ore body sulfides, which are found in a steep-sided elliptical embayment (representing the final embayment geography after thermal erosion). The main orebody is composed of massive sulfides that thermally eroded sideways into the older basalt up to 25m away from the steep embayment margin, forming a pinchout that surrounds the embayment completely. Inside the embayment massive sulfides are overlain by two layers of net-textured sulfides.

Tenors of elements that are compatible in mono-sulfide solid-solution (MSS) are concentrated at the orebody's margin whereas incompatible elements are concentrated in a small area in the centre. This is the result of fractional crystallization where MSS cumulate formed at the margin and pushing a melt boundary layer, containing the incompatible elements, towards the centre.

The Co tenor of massive sulfides is 1000-4000 ppm without significant variation. Pentlandite, the main Co-bearing mineral contains 4000-5500 ppm Co in most parts of the orebody and only in that central area drops to 200 ppm over a short distance. This, in combination with the textures of composite Co-bearing arsenide-telluride grains, suggest that in the final stages of crystallization an immiscible Pt-Pd-Co-As-Te-Bi melt forms, prior to pentlandite formation. The total volume of this area representing the high-fractionated sulfide and Pt-Pd-Co-As-Te-Bi melts is less than 1% of the overall sulfide volume of Moran.

The net-textured layer immediately above massive sulfides contain higher tenors of MSS-incompatible elements compared to massive sulfides and represents the unfractionated sulfide melt prior to MSS formation. This basal layer formed by the classical “billiard ball model” by Tony Naldrett, whereas the upper layer formed from sulfides that infiltrated the olivine cumulate and replaced interstitial silicate melt, which is evident by cauliflower-like textures on its basal contact. The second net-textured sulfides were entrained and carried from further upstream in the lava flow.

## **The Avebury Nickel deposit, Tasmania, Australia: New Insights into the Genesis of a Significant Unconventional Nickel Sulfide deposit**

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The Avebury Ni deposit, which has a resource of 22 million tonnes @ 0.97% Ni, occurs at the contact of a Cambrian ultramafic sill and Proterozoic volcanogenic sediments and lies within the contact aureole of the ~370 Ma Heemskirk Granite. Much of the mineralization, which is dominated by pentlandite with lesser amounts of pyrrhotite but significant amounts of magnetite, occurs in skarns that replaced the ultramafics or, to a lesser extent, in skarns developed in the volcanogenic sediments. The remainder of the Avebury mineralization occurs in the serpentinitized dunites. The Avebury deposit has much lower Cu and PGE than magmatic Ni-Cu sulfide deposits. Fluids from the granite overprinted the ultramafic resulting in highly elevated Bi, As, Sb, Mo and W in both mineralized and sulfide-poor ultramafic host rock. With the exception of Pd, there are strong to good correlations between Ru, Rh, Ir and Pt with Cr. The total absence of any form of correlation between Ru, Ru, Ir and Pt with Ni, as well as the low contents of these PGE in the Avebury Ni sulfide ores, rules out the possibility that Avebury is a strongly metasomatized magmatic Ni sulfide deposit. The absence of any significant Ni depletion in the unmineralized ultramafics as well as the elevated Cu and Pd contents of the mineralization suggests that these cannot have been the source of the Ni in the Avebury deposit as low sulfide ultramafic rocks have very low Cu and Pd. Evidence that the Ni mineralization is hydrothermal is provided by strong correlations between Au and Ni as well as between Sb and Ni. The strong correlation between Pd and Ni suggests that both were sourced from magmatic sulfides at depth below Avebury. It is therefore suggested that magmatic Ni-Cu-PGE sulfides lie somewhere at depth within the plumbing system of the Avebury Ni sulfide mineralization. It is probable that the S in the Avebury sulfides which have an average  $\delta^{34}\text{S}$  value of  $17.3 \pm 1.1$  ‰, was sourced either from the Heemskirk Granite, which has an average  $\delta^{34}\text{S}$  value of  $9.8 \pm 3.7$  ‰, or from the country rocks traversed by the granitic fluids that have an  $\delta^{34}\text{S}$  value of 18.9 ‰. The S isotope composition of the Avebury sulfides contrast sharply with those of magmatic Ni-Cu-PGE sulfides in Proterozoic gabbro sills at the nearby Melba Flats Ni deposit; the sulfides in these sills have an average  $\delta^{34}\text{S}$  value of  $1.5 \pm 0.2$  ‰.

## **TABS–sulfide liquid immiscibility and PGE nanonuggets**

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PGE deposits are characterised by discrete PGE minerals (PGM), often with TABS (Te–As–Bi–Sn–Sb), closely associated with sulfide minerals. Current understanding of their formation includes strong equilibrium partitioning of PGE and TABS into sulfide liquids at high temperatures, with later exsolution during cooling.

In order to test that hypothesis, we conducted high pressure and temperature experiments (5 kbar and 1100 °C) in piston cylinder apparatus. Starting materials were a mixture of silicate glass, Fe–Ni–Cu-sulfides, Bi (TABS proxy), and the PGE. Run durations ranged from 4 to 17 hours, and the experiments were quenched to near room temperature in ~10 seconds.

Nanoscale electron imaging and element mapping revealed that sulfide and bismuthide liquids are immiscible, with the PGE preferentially partitioning into bismuthide liquids. We also find abundant PGE nanonuggets coating sulfide droplet exteriors, suggesting the PGE appear to be insoluble in sulfide liquids. Similar immiscibility and insolubility textures also occur within sulfide liquids.

Our results are consistent with natural observations of sulfide–PGE–TABS association, but indicate that the underlying mechanism may be different to the currently accepted model. Extremely high sulfide/silicate partition coefficients for the PGE may be an analytical artifact, with the PGE mechanically attaching to sulfide liquids instead of dissolving in them. Instead, PGE are concentrated in immiscible TABS liquids - a primary high temperature feature, rather than exsolving during cooling.

## What controls the PGE content of porphyry Cu deposits?

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Porphyry Cu deposits can contain economic concentrations of PGE, namely Pd and Pt, as well as other critical and precious metal by-products, including the chalcophile elements Au, Ag, Te, Se and Bi. Porphyry Cu deposits in post-subduction settings have been proposed to be enriched in chalcophile elements when compared to those in subduction-related settings due to the dissolution of chalcophile-enriched residual sulfides in subduction modified subcontinental lithosphere.

We test this by presenting whole rock assay and PGE data with in situ LA-ICP-MS trace element data from sulfide minerals from three porphyry Cu deposits: the Skouries Cu-Au-(PGE) porphyry deposit, Greece, and the Muratdere Cu-Au-Mo porphyry deposit, Turkey are both post-subduction, while the El Teniente Cu-Mo porphyry deposit, Chile, is subduction-related. Comparing these against a newly compiled global dataset of trace element concentrations in sulfides from 18 other porphyry Cu deposits we show post-subduction porphyry Cu deposit sulfides are relatively enriched in Bi, Sb, Te and Se compared to sulfide minerals from subduction-related deposits. However, although some critical and precious metals (Ag, Bi and Se) are mainly hosted in sulfide ore minerals, others (Au, Te, Pd and Pt) are predominately hosted in accessory minerals.

Whole rock data shows that while the Skouries and Muratdere deposits are enriched in Au compared with El Teniente, not all post-subduction deposits are Te or PGE enriched, with PGE enrichment independent of tectonic setting. We propose that PGE enrichment in porphyry Cu deposits is controlled by the availability of Te and other semi-metals to form a semi-metal melt which concentrates and transports PGE.

## **Distribution of platinum group elements in the New Afton alkalic Cu-Au porphyry deposit, Kamloops, British Columbia**

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The mantle-derived mafic magmas parental to porphyry deposits commonly contain far more Pt and Pd than Au, and yet, historically, Au-rich alkalic porphyry deposits have not been considered as major carriers of PGE and are seldom assayed for precious metal concentrations apart from Ag and Au. There may exist a Pd-rich porphyry end member deposit type that has escaped recognition because it is not spatially associated with ore-grade Cu or Au mineralization. Interest in the potential of precious metal-rich alkalic porphyry deposits as sources of PGE has grown over the past few decades since elevated concentrations of Pt and Pd were discovered in alkaline porphyry rocks of the North American Cordillera, the Alpine-Balkan-Carpathian Dinaride belt of eastern Europe, and the Philippines, although the hallmarks of Pd-mineralized porphyry systems are enigmatic.

New Afton is an alkalic Cu-Au porphyry deposit situated 10 km west of Kamloops, British Columbia, within the Quesnel island arc terrane, a Late Paleozoic to Mesozoic arc complex in the Intermontane Belt of the Canadian Cordillera. Primary Cu-Au hypogene mineralization at New Afton is associated with biotite-dominant potassic alteration in mafic to intermediate volcanic rocks that have been affected by fluids released along structures related to a series of monzonite porphyry dikes with abundant miarolitic cavities. Copper mineralization is present as chalcopyrite and locally as chalcopyrite + bornite, showing a close spatial relationship to the monzonite intrusions. Gold is present as small inclusions of native Au and electrum in chalcopyrite and pyrite. Bulk rock and sulfide minerals from New Afton were analyzed for Pd, Pt, and Au concentrations and the presence of platinum group minerals (PGM). Fire assay data show a range of concentrations of Pd between 0.5 to 33600 ppb, Pt between 0.2 to 37800 ppb, and Au between 3 and 18600 ppb. The PGMs temagamite ( $\text{Pd}_3\text{HgTe}_3$ ), isomertieite ( $\text{Pd}_{11}\text{Sb}_2\text{As}_2$ ), mertieite-II ( $\text{Pd}_8[\text{Sb},\text{As}]_3$ ), and cooperite ( $[\text{Pt},\text{Pd}]_2\text{S}$ ) were identified in most samples with elevated Pt and Pd ( $> 400$  ppb). Palladium grades are highest close to the main monzonite porphyry bodies, tending to wrap around the intrusions, but the porphyry itself is unmineralized. LA-ICP-MS analysis shows that Ni  $\pm$  Co-rich pyrite is the main host of PGE at New Afton; concentrations of Pd and Pt in pyrite range from below detection limit to 30.8 ppm and from below detection limit to 6.9 ppm, respectively. In chalcopyrite Pd ranges from below detection limit to 13.4 ppm and Pt from below detection limit to 0.015 ppm. Precious metal ratios, particularly Pd/Au in the bulk rock samples, show that PGE mineralization may be grouped in three domains: (1) high Pd, low Pd/Au occurs throughout the deposit; (2) high Pd, high Pd/Au samples are almost entirely contained within the shallow levels of the deposit and found near or within carbonate-healed faults and structures but may also occur sparsely at depth; and (3) low Pd, variable Pd/Au are similar to Group 2 but show extensive martitization of early magnetite. These domains are interpreted as (1) representing primary PGE mineralization, related to primary hypogene Cu-Au mineralization, (2) secondary enrichment of PGE via hydrothermal redistribution, and (3) the depleted source of the secondarily enriched domains. Thermodynamic modelling shows that the co-precipitation of Pd and Ni can be explained solely through the cooling of a hydrothermal system, regardless of whether the mineralizing fluid was a brine or a low-density vapour. Pd was transported from an underlying magma reservoir into the porphyry system by a magmatic-hydrothermal fluid as a  $\text{HS}^-$  complex and incorporated in nickeliferous pyrite precipitated from cooling orthomagmatic fluids with the main Cu-Au mineralization. The initially deposited pyrite-hosted PGE were susceptible to subsequent hydrothermal remobilization and reprecipitated as platinum group minerals either in situ or as local fault-hosted enrichments in Group 2 samples. The results of our modeling show that there is a range of conditions in hypersaline brines in which Pd is expected to precipitate at temperatures well above 400 °C whereas Cu remains in solution to temperatures closer to 300 °C. The effect is accentuated in K-rich systems. It is therefore possible that under some circumstances in Cl-rich potassic magmas hydrothermal Pd mineralization might occur in a zone inside the Cu-rich hypogene shell, if one exists, perhaps not associated with obvious signs of porphyry-style mineralization.

## **The Neoarchean GT-34 Ni deposit, Carajás Mineral Province, Brazil: an atypical IOCG-related Ni sulfide mineralization**

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The GT-34 deposit, located 12 km to the SW of the Sossego copper-gold mine in the Carajás Province, northern Brazil, represents an unusual Ni sulfide mineralization. The deposit occurs along a NE-SW-trending sub-vertical shear zone marked by progressive Mg-alkalic alteration zones, predominantly hosted in granitic and locally in granodioritic to tonalitic orthogneisses. Initial alteration zones result in unique scapolite-orthopyroxene assemblage, which is partially preserved within pervasive hornblende-chlorapatite  $\pm$  plagioclase replacement zones. Nickel mineralization occurs mainly as matrix-supported breccias characterized by a pentlandite-pyrrhotite-rich matrix and rounded fragments chiefly of hornblende and chlorapatite. Irregular stockworks and net textured veins containing chalcopyrite-pentlandite are less common. Phlogopite  $\pm$  talc  $\pm$  actinolite alteration and late-stage veinlets crosscut the previous alteration zones and the mineralization. The phlogopite  $\pm$  talc  $\pm$  actinolite alteration occurs as irregular veins and chalcopyrite-pyrrhotite-magnetite are commonly observed where such alteration intersects the Ni mineralization. Late-stage veinlets are represented by K feldspar-epidote-chlorite-calcite and quartz-albite-chlorite-calcite-epidote veins, both containing minor amounts of millerite, pyrite and F-OH-apatite. High-resolution SIMS U-Pb zircon geochronology obtained for the GT-34 deposit revealed an age of  $2828 \pm 4$  Ma for zircon grains inherited from the host orthogneisses. The timing of the mineralization altered zircon grains from the scapolite-orthopyroxene and phlogopite  $\pm$  talc  $\pm$  actinolite alteration zones, is attributed to an age interval between 2751 and 2720 Ma. Although poorly constrained, the geochronological data corroborate a Neoarchean age for the GT-34 Ni mineralization, similar to that of other IOCG deposits in the Carajás Province and coeval with the bimodal magmatism in the area. The atypical orthopyroxene-marialite mineral chemistry support a metasomatic crystallization at high temperatures ( $>700^\circ\text{C}$ ), low  $a_{\text{H}_2\text{O}}$  ( $< 0.5$ ) and pressures between 5 and 7 kbar. Hypersaline fluids, as the ones described for the IOCG deposits in Carajás at such P-T conditions, would enable the orthopyroxene-marialite crystallization, as supported by experimental studies available in the literature. Mineralogical and geochemical considerations on the nature of the Ni sulfide mineralization points toward a metasomatic origin, feasible with the predicted P-T-fluid scenario for the hydrothermal alteration. Such conditions raise the initial temperature and pressure estimates of the IOCG metasomatic alteration by at least  $200^\circ\text{C}$  and pressure up to 7 kbar, making it the hottest and probably deepest IOCG-related metasomatic alteration known to date for Carajás.

## Unusual Ni sulfide deposits within the Neoarchean Carajás IOCG System – magmatic or hydrothermal?

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Hydrothermal Ni-sulfides deposits constitute deposits of minor economic importance still scarcely described. They are composed of lower-temperature mineral assemblages and generally form either as polymetallic mineralizations, or representing proximal, small-scale remobilization from nearby mafic-ultramafic Ni deposits. In the Carajás IOCG System, Brazil, Ni- and PGE-bearing minerals have always been described as subordinate phases to the Cu-Au mineralization, including siegenite and pentlandite. However, Ni-sulfide mineralizations have been recently described; they form small-scale but high-grade ores and represent the Carajás IOCG System's striking feature. We present and compare mineralogical, textural, and sulfur isotopic data from the GT-34, Castanha, and Jaguar deposits to discuss the nature (magmatic or hydrothermal) of these mineralizations. The three investigated deposits consist of lens-shaped, steeply dipping, elongated ore bodies occurring along regional-scale shear zones. These deposits are spatially associated with IOCG-deposits and display similar paragenetic sequences, marked by progressive alkali-Fe alteration halos. The mineralization occurs mainly as polymictic matrix-dominated breccias, veins, and replacement-type mineralizations, hosted chiefly by mylonitic intrusive or subvolcanic felsic rocks. The alteration and ore assemblages present textures suggestive of syn-kinematic crystallization. Each deposit hold its particularities: i) the GT-34 deposit represents the first description of hydrothermal scapolite-orthopyroxene-bearing rocks, which hosts the Ni-Fe sulfides; ii) in the Castanha deposit, carbonate and apatite are abundant phases occurring together with ore; and iii) the Jaguar deposit, conversely, is magnetite-dominated and differs due to its F-rich signature; moreover, it is the only Ni-sulfide deposit located nearby to a mafic-ultramafic intrusion. In all cases, however, the primary mineralization is characterized by varying proportions of Ni pirrotite±pentlandite±pyrite±magnetite, forming textures identical to that observed in magmatic Ni-Cu-PGE sulfide ores. Pentlandite represents the primary Ni-ore mineral and occurs forming blocky, individual grains, or flame-like exsolutions in pyrrhotite crystals. Pyrite-millerite-chalcopyrite constitutes a late hydrothermal assemblage; galena and sphalerite are associated with this later alteration, when present. The near-zero  $\delta^{34}\text{S}_{\text{V-CDT}}$  values of the GT-34 (-3.2 to +0.36 ‰) and Castanha deposits (+0.58 to +2.17 ‰) suggests a magmatic-derived sulfur source. The spread of  $\delta^{34}\text{S}_{\text{V-CDT}}$  values observed in the Jaguar deposit (+0.63 to +7.19 ‰) may be explained by sulfur disproportionation linked to the pervasive Fe-metasomatism and magnetite crystallization, prior to sulfide precipitation, and no external sulfur source is requested. Combined mineral alteration sequences, deposit geometry, structural control, as well as spatial and temporal association with Neoarchean IOCG deposits in the Carajás Mineral Province, suggests that the GT-34, Castanha, and Jaguar deposits are part of the IOCG Carajás system and may represent the missing link between orthomagmatic and magmatic-hydrothermal deposits. The transport by flotation on hydrothermal vapor bubbles would facilitate the upward mobility of the sulfide liquids and metals and the deposition at shallower crustal levels.



## **Cu (Ni, Au, PGE) deposits of the Curaçá Valley – products of complex magmatic and post-magmatic processes?**

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Ero Copper acquired Mineração Caraíba S.A. (“MCSA”) in 2016 following over 30 years of mining at Caraíba and satellite deposits. Since 2017, Ero has conducted extensive exploration (~650,000 m of drilling) in the Curaçá valley extending existing Cu deposits, and defining new zones of Cu mineralization. Mining continued at Pilar (Caraíba) with new reserves and resources at depth, and began at the Vermelhos, approximately 80 km north of Pilar, again with new reserves and resources. Numerous other targets have been tested with promising results and additional resources outlined.

Magmatic Cu (Ni) sulfide, iron oxide Cu-Au (IOCG), and hybrid models have been proposed previously (e.g., Maier and Barnes, 1996; Garcia et al., 2018) reflecting the complexity in the district. The association of sulfide mineralization with orthopyroxenite intrusions favours the magmatic model, but as noted by previous workers, low concentrations of Ni, significant bornite, and abundant phlogopite associated with sulfides are unusual features.

Ero Copper has completed extensive surface and underground mapping, drilling and core logging, and limited petrography that confirms the following:

- Cu sulfide mineralization is hosted predominantly by orthopyroxenite bodies that cut gneissic fabrics; orthopyroxenite is locally deformed.
- Minor mineralization occurs in other members of the mafic-ultramafic suite (peridotite, norite, gabbro) and locally within gneissic wallrocks.
- Phlogopite +/- carbonate occurs with sulfides in orthopyroxenite and gneiss; K-Ca-Na-rich alteration also occurs in proximity to mineralization and regionally.
- Chalcopyrite and bornite, separately and as complex intergrowths, are dominant with concentrations of pyrrhotite and pentlandite related to zones of Ni-rich mineralization; elevated PGE and Au occur in several areas exhibiting a variety of styles of mineralization; locally abundant oxides (chromite, ilmenite and magnetite) are associated with sulfides.

There are a variety of potential magmatic processes to explain for the Cu-dominant mineralization. The current working hypothesis invokes low degree partial melts, but regardless, protracted sulfide fractionation under regional high P-T metamorphic conditions was a probable mechanism for further separation of Cu, Ni and PGE-Au. Volatiles were clearly important in this process, explaining the abundance of phlogopite-carbonate. In addition, fluids may have been generated by granite-pegmatites and syenites in the region, at least some of which appear to be contemporaneous with mafic-ultramafic magmatism and sulfide crystallization. These fluids may have modified, remobilized and added mineralization.

## **Epigenetic hydrothermal Ni mineralization of the VW Zone, Junior Lake, Ontario, Canada**

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The VW Zone is an enigmatic 1.1 Mt Ni sulfide deposit grading 0.63% Ni and 0.07 % Cu which is hosted by metasedimentary and metavolcanic rocks of the Wabigoon Subprovince of the Archean Superior Province in Ontario, Canada. The host sequence comprises volcanoclastic metasediments, silicate and sulfide-facies iron formation, mafic tuff breccias and lapilli tuffs, komatiitic and basaltic lava flows, basaltic dykes and sills. Komatiite at the base is overlain by almost 20 m of fine-grained sediment probably composed primarily of volcanoclastic material and possibly some exhalative silicate iron formation and cherty sulfide iron formation. The sediments are overlain by a stack of brecciated picritic basalt flows and minor intercalated sediments about 45 m thick. The brecciated picritic basalt ranges from massive fine-grained green picritic basalt traversed by a random network of fractures to obviously brecciated material in which the basalt forms clasts up to tens of cm across with jagged margins, sitting in a matrix of greyish green quartz, carbonate and actinolite. The margins of the fractures and breccia clasts are mantled by biotite which forms millimetric books showing random orientations. The lower portion of the basalt breccia is mineralized with pentlandite and Ni-rich pyrite and pyrrhotite lacking complementary Cu or PGE of any significance. Whole rock grades locally exceed 2% Ni, and long intervals are present in some holes with average grades of order 0.5% Ni. The sulfide in this context is almost entirely within the matrix of the breccia, intergrown on the mm-scale with the quartz, ferroan ankerite, and actinolite gangue minerals. The intimate association of nickeliferous pyrite, carbonate minerals, quartz, and pentlandite is not consistent with a magmatic origin for the Ni mineralization, but would suggest a hydrothermal origin.

The deposit formed in a picritic lava flow during hydrothermal alteration of the doleritic to pyroxenitic interior of the flow and simultaneous deposition of carbonate-plagioclase-biotite-sulfide veins in the open spaces of the glassy or aphanitic flowtop breccia. Alteration was accompanied by the introduction of SiO<sub>2</sub>, CaO and Na<sub>2</sub>O and the removal of FeO from the interior of the flow, and the addition of CaO, Na<sub>2</sub>O, NiS and FeS to the mineralized portions of the flow exterior. This alteration process was marked by the new growth of plagioclase and carbonate minerals. The entire volcanoclastic-sedimentary sequence including the mineralized picritic lavas was subjected to intense carbonate alteration. Peridotites which probably already had been serpentinized were replaced by talc-carbonate ± chlorite, and pyroxenites were replaced by carbonate + tremolite. A plausible suggestion is that the carbonate alteration destroyed Ni-bearing silicate minerals in the picrites and underlying peridotites, releasing Ni into the same fluids that were responsible for the formation of the veins of carbonate and plagioclase. There was a change in sulfidation state from the flow interior to the margins, marked by a change from pyrite-dominated assemblages in the interior to pyrrhotite-dominated assemblages at the margins. The Ni-sulfide minerals were deposited preferentially in the lower fS<sub>2</sub> environment in the flow margins, in the open space provided by the presence of the hyaloclastic breccias

The VW zone appears to have formed in a sub-seafloor setting in response to CO<sub>2</sub>-rich fluid flow through an underlying package of rocks including serpentinites. The unusual association of Ni sulfides with a hydrothermal vein stockwork in a seafloor setting invites comparisons with ancient Ni-bearing Cu-sulfide VMS deposits including the Paleoproterozoic Outokumpu district of Finland as well as the Cambro-Ordovician Eastern Metals deposit in Quebec and Sykesville district in Maryland. Similar deposits have been observed forming on the Mid-Atlantic Ridge at the Rainbow and Logatchev hydrothermal vent fields. The outstanding difference between the VW zone and the analogues suggested above is that although the Ni-rich vein stockwork corresponds moderately well to similar stockworks in the other modern and ancient deposits the VW zone lacks a large Cu-rich massive sulfide deposit above the stockwork.