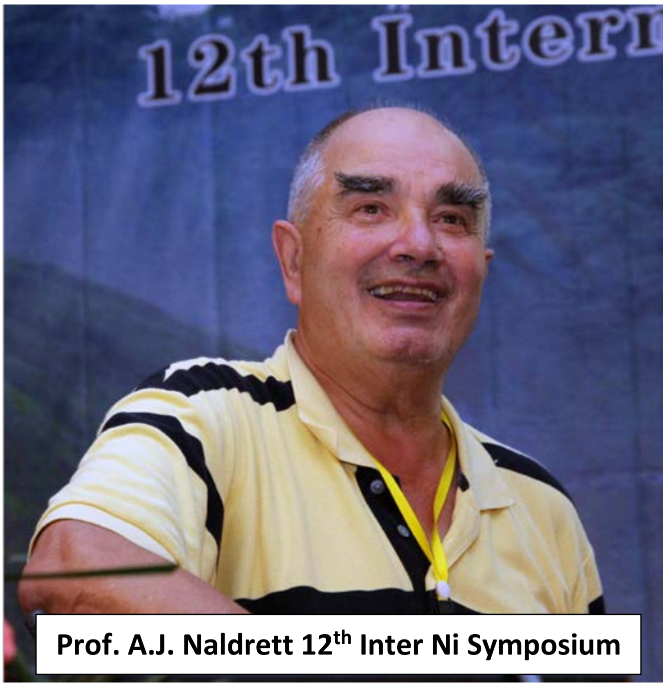
ABSTRACT VOLUME AND PROGRAM

PART A OF 14TH INTERNATIONAL NICKEL-SYMPOSIUM AND MEMORIAL TO PROF. A.J. NALDRETT

VIRTUAL MEETING HELD 28TH AUGUST, 4TH SEPTEMBER, AND 11TH SEPTEMBER 2020.

EDITORS – SARAH-JANE BARNES AND EDUARDO MANSUR

EAGLE Ni-Cu Mine Michigan



Prof. A.J. Naldrett 12th Inter Ni Symposium

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PROVISIONAL PROGRAM

28th August 2020

Time Toronto	Speaker	Title
7:00	Sarah Barnes	OPENING REMARKS
7:05	Steve Barnes	MEMORIAL FOR PROF. A.J.NALDRETT

	28th August	*Mid Continental Rift and Exploration*
	Chairs	*Matt Brzozowski and Xin Ding*
7:15	MILLER, J.	GEOLOGY, MINERAL DEPOSITS, AND TECTONOMAGMATIC EVOLUTION OF THE MIDCONTINENT RIFT IN THE LAKE SUPERIOR REGION
7:30	BENSON, Erin	S ISOTOPE HETEROGENEITY AT THE EAST EAGLE NI-CU-PGE DEPOSIT, NORTHERN MICHIGAN
7:45	CRUDEN Alexander	STRUCTURE AND EMPLACEMENT OF THE EAGLE PERIDOTITES AND THEIR ASSOCIATED NI-SULFIDE MINERALIZATION, MICHIGAN, USA
8:00	MAHIN, Robert A	EXPLORATION AND DISCOVERY OF THE EAGLE AND EAGLE EAST NI-CU-CO-PGE DEPOSITS, UPPER PENINSULA, MICHIGAN
8:15	ESSIG, Espree E	MAGNETIC SUSCEPTIBILTY OF CONTACT METAMORPHOSED COUNTRY ROCK SEDIMENTS AS AN EXPLORATION TOOL FOR MINERALIZED PERIDOTITE CHONOLITHS: EAGLE AND EAGLE EAST NI-CU-CO-PGE DEPOSITS, UPPER PENINSULA, MICHIGAN
8:30	MILLER, J.	LITHOSTRATIGRAPHY, MINERALIZATION, AND PETROGENESIS OF THE MCR-RELATED SUNDAY LAKE INTRUSION, NW ONTARIO
8:45	Discussion	

		Exploration and others
9:00	KAAVERA Jacob	SULFIDE-SILICATE TEXTURAL RELATIONSHIP IN DISSEMINATED Ni-Cu-PGE MINERALIZATION OF MOLOPO FARMS COMPLEX, TUBANE AREA, SOUTHERN BOTSWANA
9:15	SCHONEVELD, Louise	NEW POTENTIAL INDICATOR MINERALS FOR MAGMATIC SULFIDE MINERALISATION
9:30	MANSUR, Eduardo	TRACE ELEMENTS IN PYRRHOTITE, PENTLANDTE, CHALCOPYRITE AND PYRITE FROM MAGMATIC SULFIDE DEPOSITS: AN OVERVIEW
9:45	WRAGE, Jackie	SULFIDE AND SULFATE SATURATION OF DACITIC SILICATE MELTS AS A FUNCTION OF OXYGEN FUGACITY
10:00	GOLDIE, Raymond	NSR: A TOOL FOR EVALUATING NICKEL-COPPER-PGE SULFIDE DEPOSITS, AND FOR FINANCING EXPLORATION
10:15	Discussion	
10:30	End	

	4th September	**Sudbury Nova Jinchuan Miscellaneous**
Time Toronto	***Chairs***	***Katie McFall and Eduardo Mansur***

7:00	LESHER, C Michael	GENESIS OF Ni-Cu-PGE MINERALIZATION IN THE SUDBURY IGNEOUS COMPLEX: IMPACT DEVOLATILIZATION, THERMOMECHANICAL EROSION, AND DYNAMIC UPGRADING OF SULFIDE XENOMELTS
7:15	BAURIER AYMAT, Sandra	CHARACTERIZATION AND LOCALIZATION OF BRECCIA-HOSTED NI-CU-PGE MINERALIZATION IN THE CRYDERMAN AREA, SUDBURY IGNEOUS COMPLEX, ONTARIO*
7:20	PETERS, Dustin	CHARACTERIZATION AND FORMATION OF CONTACT-TYPE Ni-Cu-PGE MINERALIZATION IN THE NORTH RANGE OF THE SUDBURY IGNEOUS COMPLEX, ONTARIO*
7:25	SEIBEL, Henning VL	MODELS AND PROCESSES OF OFFSET DIKE FORMATION IN THE SUDBURY IGNEOUS COMPLEX*
7:30	Discussion	
7:45	RENNICK, Steven.	STRUCTURAL AND LITHOLOGICAL CONTROLS ON THE EMPLACEMENT OF THE NOVA-BOLLINGER DEPOSIT, ALBANY FRASER OROGEN, WESTERN AUSTRALIA
8:00	CAVE, Ben J	STRATIGRAPHY OF THE INTRUSIONS HOSTING THE NOVA-BOLLINGER NI-CU-CO SULFIDE ORE DEPOSIT, ALBANY-FRASER OROGEN, WESTERN AUSTRALIA.
8:15	TARANOVIC, Valentina	NOVA-BOLLINGER NI-CU-CO DEPOSIT, ALBANY-FRASER OROGEN, WESTERN AUSTRALIA: MULTI-SCALE PROCESSES IN THE DEEP CRUST
8:30	Discussion	
8:45	DUAN, Jun	A COMBINED STUDY OF MULTIPLE SULFUR AND IRON ISOTOPES OF THE JINCHUAN MAGMATIC NI-CU-PGE SULFIDE DEPOSIT IN WESTERN CHINA
9:00	DING, Xin	MG AND C-O ISOTOPE VARIATIONS DURING MAGMA-CARBONATE INTERACTION AT JINCHUAN: IMPLICATION FOR MINERALIZATION
9:15	VIRTANEN Ville	BLACK SHALE PARTIAL MELTING EXPERIMENTS PROVIDE INSIGHT INTO S, C, AND CU ASSIMILATION PROCESSES IN DULUTH COMPLEX, MINNESOTA
9:30	SMITH, William D.,	IS THE LABRADOR TROUGH PROSPECTIVE FOR MAGMATIC NI-CU-PGE SULPHIDE DEPOSITS?
9:45	HOULÉ, Michel G.	EMPLACEMENT HISTORY OF THE NEOARCHEAN CR-NI-BEARING ESKER INTRUSIVE COMPLEX, RING OF FIRE INTRUSIVE SUITE, NORTH-CENTRAL SUPERIOR PROVINCE, ONTARIO, CANADA: INSIGHTS FROM U- PB ZIRCON GEOCHRONOLOGY
10:00	BLANKS, Daryl E,	THE EVOLUTION OF THE DYNAMINC MUNALI NI-CU-PGE DEPOSIT, ZAMBIA
10:15	HOLWELL, David	MAGMATIC SULFIDES DID NOT SIMPLY WALK IN TO MORDOR: SO HOW DID THEY GET THERE?
10:30	Discussion	

11th September PLATINUM-GROUP ELEMENTS

Time Toronto	***Chairs***	***LOUSIE SCHONVELD AND VALENTINATARANOVIC***
7:00	MAIER, Wolfgang,	FORMATION OF THE FLATREEF DEPOSIT, NORTHERN BUSHVELD, BY HYDRODYNAMIC AND HYDROMAGMATIC PROCESSES
7:15	MANSUR, Eduardo	MODELLING OF THE DISTRIBUTION OF TE, AS, BI, SB, SN (TABS) AND SE IN THE MERENSKY REEF AND THE IMPLICATION FOR PGE COLLECTION MECHANISMS IN MAGMATIC SULFIDE DEPOSITS
7:30	BENSON, Erin	ISOTOPIC MODELING OF MIXING IN THE BUSHVELD COMPLEX AND SUBDUCTION ZONE ANALOGS
7:45	MCFALL, Katie A.	EARLY HYDROTHERMAL MODIFICATION OF THE AURORA AND WATERBERG PTM MAGMATIC SULPHIDE NI-CU-PGE DEPOSITS IN THE NORTHERN BUSHVELD COMPLEX, SOUTH AFRICA

8:00	CHAUMBA Jeff	ORIGIN OF ROCKS AND ASSOCIATED SULFIDE MINERALIZATION STRADDLING THE MAIN SULFIDE ZONE OF THE NGEZI SUBCHAMBER, GREAT DYKE, ZIMBABWE
8:15	Discussion	
8:30	FIFER, Caleb	NI ISOTOPE VARIATIONS OF THE J-M REEF, STILLWATER COMPLEX, MONTANA
8:45	JENKINS Christopher	COMPOSITION OF THE J-M REEF MINERALIZATION, STILLWATER COMPLEX, MONTANA, USA
9:00	BARNES, Stephen	ORIGIN OF THE PGE-CHROMITITE ASSOCIATION IN LAYERED INTRUSIONS
9:15	BARNES Sarah-Jane	MAJOR AND TRACE ELEMENT COMPOSITIONS OF CHROMITES FROM THE STILLWATER, BUSHVELD AND GREAT DYKE INTRUSIONS COMPARED WITH CHROMITES FROM KOMATIITES, BONINITES AND LARGE IGNEOUS PROVINCES
9:30	Discussion	
9:45	BRZOZOWSKI, Matthew J.	CU ISOTOPE FRACTIONATION IN CONDUIT-TYPE CU–PGE MINERALIZATION IN THE EASTERN GABBRO, COLDWELL COMPLEX, CANADA
10:00	GOOD, David J.	CHANGING OUR UNDERSTANDING OF THE COLDWELL COMPLEX IN THE CONTEXT OF THE MCR THROUGH PASSIVE SEISMIC SURVEY, DIAMOND DRILLING AND GEOCHEMISTRY
10:15	Discussion	

MAJOR AND TRACE ELEMENT COMPOSITIONS OF CHROMITES FROM THE STILLWATER, BUSHVELD AND GREAT DYKE INTRUSIONS COMPARED WITH CHROMITES FROM KOMATIITES, BONINITES AND LARGE IGNEOUS PROVINCES.

Barnes, Sarah-Jane, MANSUR,, Eduardo, PAGÉ, Philippe, MERIC Meric and ARGUIN, Jean-Philippe Arguin, Sciences de la Terre, Université du Québec à Chicoutimi, Chicoutimi, G7H2B1 Canada, sjbarnes@uqac.ca

The composition of the magmas from which the chromites that form the massive chromite layers of the Stillwater, Great Dyke and Bushveld Complexes are of interest both to understand the economic importance of the resources in the layers (Cr and PGE), but also in understanding how these layers form. Magmas that have been suggested as parental to the intrusions are boninites or crustally contaminated komatiites. In recognition of the continental setting of the Bushveld and Great Dyke another magma type that could be considered is picrite associated with continental flood basalts. In order to investigate whether any of these magmas are suitable parental magmas for the chromites we have determined major and trace elements in komatiites of low metamorphic grade, boninites and chromites from low-Ti and high-Ti picrites of the Emeishan Provence.

In terms of major and minor elements none of the chromites from the layered intrusions match boninite chromites. The Great Dyke chromites are similar to chromites from komatiites. The chromites the Bushveld are slightly more evolved with higher Ti contents and lower Cr# and resemble the chromites from the low-Ti picrites of Emeishan. The Stillwater chromites have similar Ti contents to the Emeishan low-Ti picrites, but have lower Cr#. Their compositions resemble chromite compositions reported from picrites of the North Atlantic Igneous Provence.

Hafnium, Ta, Cu, Sn, Sc, Ti, Mn, Ni, Co, Mn, Ga, V and Zn were determined by LA-ICP-MS. Podiform chromites from boninites are depleted in most trace elements and none of the intrusions chromites resemble them. The chromites from the Great Dyke have trace element concentrations similar to komatiite, but lower Cu and high Sn contents. The Bushveld and Stillwater chromites are richer in Al, Ga, V and Ti than the komatiite chromite and are depleted in Cu. The trace element concentrations patterns resemble the chromites form the low Ti-picrites except the picrites are richer in Hf, Ta and Cu.

The chromite compositions suggest that boninite magmas are not involved in forming the chromites from layered intrusions. The Great Dyke chromites appear to have a strong komatiitic affinity. The Bushveld and Stillwater chromites formed from magmas with larger continental crustal components.

ORIGIN OF THE PGE-CHROMITITE ASSOCIATION IN LAYERED INTRUSIONS

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The close association of ore-grade concentrations of PGEs in chromite-rich rocks in layered intrusions has been much debated. PGE concentrations in stratiform reefs, with or without chromite, are always very precisely associated with sulfides, as can be demonstrated using the Maia Mapper microbeam XRF imaging technique. Grades of PGE reefs vary much less than the tenors do. The most extreme tenors are seen in newly nucleated sulfides formed from previously sulfide undersaturated magma. Chromite makes an ideal substrate for the nucleation of both sulfides and PGE minerals (PGMs). A crucial piece of the puzzle is that sulfides have nucleated in situ in chromite-rich cumulates on overhanging and undercut surfaces in Merensky Reef potholes. This leads us to propose a model whereby chromite nucleates and grows in situ along erosional unconformities, from previously undersaturated magma containing “normal” PGE contents. Initial chromite growth causes transient local boundary layer saturation in both sulfide liquid and PGMs. A given interval of chromitite needs at least 100 and possibly 1000 times its own mass of magma; hence, if a chromitite contains 1% sulfide, that sulfide reacts at R factors of 10^4 to 10^5, corresponding to the Merensky and JM reefs, but still too low for the most extreme tenors of some chromite-hosted reefs. In these cases, we postulate that continuing interaction with bulk S-undersaturated magma cause partial or even complete redissolution of sulfides, stabilizing solid PGMs and generating ultra-high tenors. This exact process can also explain the anomalously high abundance of PGM in certain ophiolitic chromitites, notably Shetland, and may be applicable to the Heazlewood River Os-Ir occurrence in Tasmania.

NOVA-BOLLINGER NI-CU-CO DEPOSIT, ALBANY-FRASER OROGEN, WESTERN AUSTRALIA: MULTI-SCALE PROCESSES IN THE DEEP CRUST

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Ore forming processes involve the redistribution of heat, mass and momentum by a wide range of processes operating at different time and length scales. The most recent major nickel sulfide discovery in Australia, the Nova-Bollinger system in the Albany-Fraser Orogen, makes an excellent case study of multi-scale processes taking place at high temperatures in the deep crust. Processes operating on timescales from days to millions of years can be identified in the ores and host rocks at length scales from km to hundreds of metres. Microtextures developed within the host intrusions (dendritic olivines and sector-zoned pyroxenes) record an initial period of supercooled crystallisation in a chonolith-style small intrusion, followed by prolonged slow cooling near the solidus giving rise to extensive reaction coronas and symplectites. Sulfide infiltration into country rock gneisses started at the time of emplacement of the ores into granulite gneiss wall rocks and continued over million-year timescales during the cooling and exhumation of the orogen. The unusually extensive development of off-contact ores, including infiltration ores where sulfides invade paragneiss host rocks at grain scale, was facilitated by two factors: the wall rocks were already close to their solidus temperatures at the time of emplacement; and emplacement and post-emplacement migration were accompanied by extensional deformation that included episodes of brittle fracturing driven by transient high strain rates. A key line of evidence in this interpretation is the presence of pentlandite-chalcopyrite loop textures throughout the orebody, marked by high Pd contents of the pentlandite, which is interpreted as the result of peritectic crystallisation within the sulfide melting range. The processes identified at Nova could be considered as alternatives to purely tectonic remobilisation models that are commonly applied in deposits such as Thompson where much of the ore lies within country rocks.

CHARACTERIZATION AND LOCALIZATION OF BRECCIA-HOSTED NI-CU-PGE MINERALIZATION IN THE CRYDERMAN AREA, SUDBURY IGNEOUS COMPLEX, ONTARIO*

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The Sudbury Igneous Complex (SIC) hosts one of the world's largest known resources of Ni-Cu-PGE mineralization and has been interpreted to result from a 1.85 Ga impact event. Mineralization occurs in the contact-footwall environment as magmatic breccias and brecciated footwall rocks along or near the basal contact of the SIC, and in the offset environment as radial and concentric dikes emplaced into the footwall rocks. Although the geology of the SIC is reasonably well understood, the ore-forming mechanisms and controls are still debated and the mechanisms controlling the internal textures and fabrics of the contact ores have received little attention. Sublayer norite (SLNR) and footwall breccia (FWBX) occur discontinuously along the basal contact of the SIC and host a significant portion of the Ni-(Cu-PGE)-bearing contact ores. The units are locally well developed on the SIC North Range but FWBX appears to be less well developed on the South Range. They are both polymictic, matrix- to clast-supported breccias containing heterometric fragments of mostly local footwall lithologies and minor exotic lithologies. The SLNR is characterized by a magmatic noritic matrix and FWBX is characterized by an anatectic matrix derived from the local footwall rocks. In both cases the matrix can be replaced by variable amounts of sulfides. The FWBX matrix coarsens towards the contact with the SIC, and mineralogy and bulk composition vary with proximity to the footwall and to the sulfide mineralization. Drill core logging in the Cryderman area, located along the SE margin of the SIC, reveals that mineralization occurs dominantly in clast-supported breccias developed in metabasalts. Intervals of inclusion massive sulfides typically occur adjacent to weakly to non-brecciated metabasaltic-metasedimentary footwall rocks. It remains undetermined whether these rocks are magmatic SLNR, anatectic FWBX, or a hybrid involving structural and tectonic processes. Petrographic, textural, and mineralogical studies will help establishing the nature of the host breccias in the Cryderman area and constrain the mechanism of formation, timing, and spatial relationships between the different rock types in contact-ore environments.

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ISOTOPIC MODELING OF MIXING IN THE BUSHVELD COMPLEX AND SUBDUCTION ZONE ANALOGS

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Crystallization of the 2.06 Ga Bushveld magma formed a 9 km (maximum) sequence of ultramafic and mafic rocks that generated a large volume of country fluid as it thermally metamorphosed a 3+ km section of previously unaltered underlying sedimentary rocks of the Transvaal sequence. Initial Sr, Nd, and Os isotopic ratios in different zones of the complex vary substantially, while mineral assemblages show extensive isotopic disequilibrium. Stable isotopic compositions, such as O and H, also show evidence of alteration from mantle signatures. Conventional explanations for this involve variable crustal contamination; one oft-overlooked possibility is contamination introduced by crustal fluids generated via dehydration of the country rock during emplacement. Using Sr and Nd as well as O and H, two-component mixing diagrams are generated between typical mantle melts and Bushveld country rock fluids. The results of these mixing calculations suggest that as a little as 1 wt. % of a country rock fluid can pull the mantle isotopic composition toward a more typical Main Zone composition. Assuming the 3.5 km Bushveld aureole generated 3-6 wt. % H_2O, this would require roughly a third to half of the vapor generated by dehydration. Along with geochemically demonstrating the viability of the country fluid circulation model, we draw analogies to certain subduction zone processes that are not fully understood. The geometry of the Bushveld Complex—hot mantle material overlying cold crustal material—is similar to that seen as subducting lithospheric slabs are heated by overlying mantle rocks. Dehydration of subduction slabs is responsible for melt generation in the mantle and the creation of volcanic arcs at the surface. The process of fluid migration out of the slab and into the mantle wedge is poorly understood; layered intrusions can lead to a better understanding of unobservable subduction zone processes such as fluid migration.

S ISOTOPE HETEROGENEITY AT THE EAST EAGLE NI-CU-PGE DEPOSIT, NORTHERN MICHIGAN

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The East Eagle Ni-Cu-PGE deposit is a conduit-type deposit located in northern Michigan, in close spatial proximity to the currently producing Eagle deposit. Massive and semi-massive sulfide mineralization at East Eagle occurs ~200 m above the contact between Proterozoic and Archean rocks. Massive and semi-massive sulfide mineralization at East Eagle is characterized by a relatively narrow range of $\delta^{34}S$ values, from 1.5 to 3.8‰. In strong contrast to these values, those from disseminated sulfides that border the massive and semi-massive mineralization define a much larger range from -4.3 to 22.8‰. The much more restricted range in $\delta^{34}S$ values recorded in the massive and semi-massive sulfide mineralization compared to the disseminated mineralization is thought to reflect isotopic exchange reactions in the conduit involving accumulated sulfide and pulses of magma containing S of mantle origin. $\Delta^{33}S$ values of all three major types of sulfide mineralization at East Eagle are near zero ‰, with most values between -0.03 and 0.03‰, suggesting no involvement of S from the Archean rocks, unlike at the nearby Eagle intrusion. The wide range in $\delta^{34}S$ values recorded in the disseminated mineralization provides strong evidence that S from Proterozoic sedimentary host rocks was involved in the mineralization. The wide range of disseminated sulfide $\delta^{34}S$ values are spatially heterogeneous as well. Meter-scale S isotopic variations, as well as variations in Pt and Pd tenor, are consistent with multiple inputs of magma, each characterized by distinct S isotope ratios. Heterogeneity of several ‰ at the cm-scale indicates that the degree of supercooling exceeded the S diffusivity, preserving small scale S isotope variability inherited from the sedimentary country rock source. Elongate, branching plagioclase grains in many of the gabbroic rocks that host the disseminated sulfide mineralization are consistent with a rapid second stage of cooling.

THE EVOLUTION OF THE DYNAMINC MUNALI NI-CU-PGE DEPOSIT, ZAMBIA

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The Munali Ni-Cu-PGE deposit is located within the Zambezi Belt in southern Zambia and appears to represent, on a geotectonic scale, a conduit style, sulfide 'breccia' deposit, situated along a major regional fault zone. The Munali Igneous Complex comprises a multi-phase composite system with an unmineralised gabbroic core, surrounded by a later marginal mafic-ultramafic breccia unit that is host to the sulfide ore. However, Munali displays many atypical features that question the applicability for the genesis of the deposit against traditional models. The complex comprises a suite of geochemically diverse mafic-ultramafic host rocks that include gabbro and Cr-poor, apatite-bearing dunite, wehrlite and rare clinopyroxenite. Sulfide mineralisation is characterised by an unusually Ni-rich, massive to semi-massive sulfide, comprised of pyrrhotite >> pentlandite > chalcopyrite ± pyrite associated with abundant carbonate-apatite-magnetite. Geochemically, the bulk sulfide displays high Ni/Cu ratios (~10) and moderate to high Pd/Ir_N ratios (~ 150 to 3500) and an extreme negative Au anomaly. The sulfide of the orebody displays consistently mantle-like S/Se ratios, yet positive, crustally-derived $\delta^{34}S$ isotopic signatures. The sulfide is hosted predominantly within three conformable sulfide sheets (between 1 to 30 m in thickness) within the mafic-ultramafic breccia unit, where it displays variable sulfide breccia textures and evidence of post-emplacement deformation. Although sulfide is most closely associated with ultramafic rocks with the presence of passive sulfide melt infiltration and brecciation, it appears to not be synchronous with ultramafic emplacement with later infiltration of sulfide, with the ultramafics representing a 'surrogate' host. The implication of sulfide representing a significantly later phase suggests that the sulfide may be sourced and/or mobilized from a younger magmatic event and subsequently emplaced within the Munali Complex.

CU ISOTOPE FRACTIONATION IN CONDUIT-TYPE CU–PGE MINERALIZATION IN THE EASTERN GABBRO, COLDWELL COMPLEX, CANADA

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Equilibrium isotope fractionation factors are expected to be small for heavy elements at high temperatures, however, chalcopyrite from the Cu–PGE sulfide deposits in the Eastern Gabbro, Coldwell Complex, Canada exhibit δ^{65}Cu values that range over 2‰. The δ^{65}Cu of chalcopyrite in the Marathon deposit ranges from -1.49 to 1.07‰, whereas chalcopyrite in the Four Dams and Area 41 deposits largely have mantle values (0.06 ± 0.2‰). Numerical modelling of δ^{65}Cu–Cu/Pd–S/Se of mineralization in these deposits suggests that i) contamination by Archean sedimentary rocks can modify Cu isotopes from typical mantle values, ii) R factors less than 100,000 can exhibit significant control on the δ^{65}Cu of sulfides, and iii) sulfide segregation exhibits no measurable control on the δ^{65}Cu of sulfides at reasonable degrees of fractionation (<0.3%). The range of δ^{65}Cu–S/Se–Cu/Pd in the Marathon deposit is attributed to the addition of Archean sedimentary Cu to a pool of sulfide liquid located at depth, followed by progressive dilution of the contaminated δ^{65}Cu–S/Se signature and decrease in Cu/Pd ratio by influxes of uncontaminated pulses of magma (i.e., increasing R factor), some of which had Cu isotope compositions heavier than the mantle. Variably contaminated and enriched (with respect to Pd) sulfides from this pool were entrained in these pulses and emplaced to form the Footwall Zone (most contaminated), Main Zone, and W Horizon (least contaminated) of the Marathon deposit. The largely mantle δ^{65}Cu, but lower- and higher-than-mantle S/Se and Cu/Pd observed at Four Dams and Area 41 were likely the result of sulfide fractionation at depth and contamination by igneous rocks that experienced S loss. This demonstrates that Cu isotopes can exhibit large fractionations at high temperature, which, when combined with other geochemical proxies, can be invaluable in characterizing magmatic–post-magmatic processes in Ni–Cu–PGE sulfide deposits and for identifying PGE-rich sulfide deposits.

STRATIGRAPHY OF THE INTRUSIONS HOSTING THE NOVA-BOLLINGER NI-CU-CO SULFIDE ORE DEPOSIT, ALBANY-FRASER OROGEN, WESTERN AUSTRALIA.

CAVE, Ben J, TARANOVIC, Valentina, BARNES, Stephen J, BERESFORD, Steve, RENNICK, Steven, CROOK, Kelsey, Independence Group, South Perth, WA 6100, ben.cave@igo.com.au

The Albany-Fraser Orogen, Western Australia, is an emerging orthomagmatic Ni-Cu-Co sulfide belt. At present, Nova-Bollinger represents the most significant discovery (2012) in the belt, with a pre-mining resource of 14.6Mt @ 2.2% Ni, 0.9% Cu, and 0.08% Co. Mineralization at Nova-Bollinger is genetically associated with ultramafic and mafic cumulate rocks that are grouped into an “Upper Intrusion” and a “Lower Intrusion”, based on spatial and textural relationships. The Upper Intrusion is a modally layered, ultramafic-mafic intrusion (2400m x 1200m x 450m) that occupies a doubly plunging synform. Modal layering typically consists of heteradcumulate lherzolites (0.2-to-100m thick), with alternating layers of mesocumulate gabbronorites/norites. A distinct zone (up to 100m thick) of ortho-to-mesocumulate mafics and ultramafics (i.e., gabbronorites, norites, poikilitic olivine-websterites, and feldspathic lherzolites) exists in a lower zone of the Upper Intrusion. This zone links the Upper Intrusion to the Lower Intrusion and hosts the largely disseminated, C5 resource (≈1.15Mt @ 0.8% Ni, 0.4% Cu, 0.04% Co). The Lower Intrusion is a zoned, ultramafic-mafic tabular chonolith that pinches-and-swells (width 45-370m; thickness 5-150m) over a length of 1300m and is semi-conformable with the easterly-dipping, western side of the doubly plunging synform. Zonation in the intrusion typically consists of a thin (<1-5m) veneer of orthocumulate gabbronorites/norites, surrounding a poikilitic orthocumulate olivine websterite core (1-60m thick). Where the chonolith swells, orthocumulate feldspathic lherzolites dominate the core of the intrusion (up to 50m thick), with olivine websterite and gabbronorite/norite zones surrounding the lherzolite core. Disseminated-to-massive sulfides are hosted within the Lower Intrusion, and together with the footwall stringer veins and massive lenses developed below the intrusion, constitute the Nova-Bollinger ore deposit.

ORIGIN OF ROCKS AND ASSOCIATED SULFIDE MINERALIZATION STRADDLING THE MAIN SULFIDE ZONE OF THE NGEZI SUBCHAMBER, GREAT DYKE, ZIMBABWE

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Constraints from mineralogy, textures, and mineral chemistry of samples from diamond drill holes that intersected the Main Sulfide Zone (MSZ), the major platinum-group element mineralization of the Ngezi Subchamber of the Great Dyke are here described and discussed. Orthopyroxene cumulates predominate the mineralogy within, and in the vicinity of the MSZ investigated, with plagioclase, clinopyroxene, and sulfide minerals occurring as intercumulus minerals. Some of the sulfide minerals occur as inclusions within orthopyroxenes. The sulfides, however, commonly occur as intercumulus phases. Additionally, phlogopite occurs as a minor phase in most samples from the investigated area. The phlogopite tends to occur in association with both sulfide and intercumulus minerals. Pyroxene ($\mathrm{En}_{98.6-42.3}\mathrm{Fs}_{23.4-0}\mathrm{Wo}_{48.0-0.2}$) types are, in order of decreasing abundance, enstatites, augites, diopsides, and pigeonites, and occur together with plagioclase ($\mathrm{An}_{77.7-48.5}\mathrm{Ab}_{49.5-19.1}\mathrm{Or}_{3.1-1.4}$) of bytownite and andesine composition. Application of two-pyroxene geothermometry to samples under study yields temperatures ranging from 864-1022^{o}C (average of 953^{o}C), which are interpreted to indicate crystallization temperatures. Biotite thermometry yields comparatively lower temperatures which cluster at 717^{o}C which we interpret to indicate the temperature of hydrothermal alteration. It is possible that original magmatic platinum-group element mineralization in the Ngezi Subchamber was subsequently concentrated during hydrothermal alteration coincident with formation of the phlogopites. The close association of biotite and sulfide minerals lends support to this interpretation.

MG AND C-O ISOTOPE VARIATIONS DURING MAGMA-CARBONATE INTERACTION AT JINCHUAN: IMPLICATION FOR MINERALIZATION

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The Jinchuan Ni-Cu deposit is one of the largest magmatic sulfide deposits in the world, but the cause of sulfide saturation is still unclear. It has been suggested that sulfide saturation in the Jinchuan magma was triggered by carbonate assimilation. We use Mg and C-O isotopes to evaluate the role of carbonate assimilation in sulfide mineralization.

The measured values of $\delta^{18}O$ and $\delta^{13}C$ for carbonate minerals from country rock marbles range from 13.15 to 21.56‰ and from -1.67 to 1.29‰, respectively. Carbonate minerals from xenoliths and hybrid rocks in the contact zone have lighter C-O isotope compositions, with $\delta^{18}O$ and $\delta^{13}C$ values from 11.30 to 15.87‰ and from -4.65 to -2.34‰, respectively. The $\delta^{26}Mg$ values of xenoliths and hybrid rocks are from -1.71 to -1.36‰, similar to the values of the marbles (-1.74 to -1.34‰).

The $\delta^{18}O$ values of pyroxene in the margin and the center of the Jinchuan intrusion vary from 5.1 to 7.8‰ and from 5.3 to 6.5‰, respectively. The higher values clearly exceed typical mantle value (5.1 ± 0.3‰). The $\delta^{26}Mg$ values of marble xenoliths and the associated hybrid rocks in the intrusion are from -1.48 to -1.35‰ and from -1.69 to -0.92‰, respectively, which are within the range of the marble country rocks. The $\delta^{26}Mg$ values of pyroxene with variable distances from the xenoliths have similar $\delta^{26}Mg$ values from -0.32 to -0.16‰, which are similar to typical mantle value (-0.25 ± 0.07‰).

The C-O isotopic variations are consistent with de-carbonation. Rayleigh fractionation modelling shows 40 to 80% CO_2 loss from xenoliths and hybrid rocks. The resultant olivine and diopside in the hybrid rocks appear to have inherited $\delta^{26}Mg$ values from the reactant dolomites. The effect of interaction between marble xenoliths and mafic magma on $\delta^{26}Mg$ variation is limited, as most of the xenoliths have $\delta^{26}Mg$ values similar to those of the marble country rocks. The results from this study reveal that C-O isotopes are better tracers for carbonate assimilation than Mg isotopes. The released CO_2 from the marble xenoliths and footwall could have infiltrated the overlying magma, increasing the $\delta^{18}O$ values of the magma, as indicated by some of the pyroxene samples we have analyzed. The role of such processes in sulfide mineralization, however, remains unclear.

A COMBINED STUDY OF MULTIPLE SULFUR AND IRON ISOTOPES OF THE JINCHUAN MAGMATIC NI-CU-PGE SULFIDE DEPOSIT IN WESTERN CHINA

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The Jinchuan Ni-Cu-PGE sulfide deposit in China is the largest single magmatic sulfide deposit in the world. It is hosted in an elongated, steeply-dipping ultramafic intrusion that was emplaced at ~830 Ma in the southwestern margin of the North China Craton. Sulfide mineralization occurs mainly as heavily-disseminated sulfides (pyrrhotite + pentlandite + chalcopyrite) in the base and center of the intrusion. The immediate country rocks of the Jinchuan intrusion are Proterozoic marbles and gneisses. It has been suggested that marble assimilation or addition of external sulfur played a critical role in sulfide saturation in the Jinchuan magma. We use a combination of multiple S and Fe isotopes to evaluate the significance of external sulfur in the deposit. The results are reported here.

The δ^{56}Fe value of one chalcopyrite analysis for the Jinchuan magmatic Ni-Cu deposit is 1.26 ‰. The δ^{56}Fe values of pyrrhotite separates from this deposit are from -1.07 to -0.33 ‰, which are significantly lower than those of this phase from other major magmatic Ni-Cu sulfide deposits in the world, such as the Noril'sk-Talnakh and Voisey's Bay deposits. Our tentative explanation for the unusually low δ^{56}Fe values of pyrrhotite in the Jinchuan deposit is the involvement of low δ^{56}Fe components in the formation or modification of this deposit.

The δ^{34}S values of sulfide minerals from the Jinchuan deposit are between -0.57 and 1.53 ‰, which are within the ranges of the mantle as well as Archean sedimentary rocks. The Δ^{33}S values of these samples are from -0.09 to 0.22‰. This range is larger than that of post-Archean sedimentary sulfides (0 ± 0.06 ‰), indicating the presence of sulfur that was derived from Archean sedimentary rocks or younger rocks that contain recycled Archean sulfur. Pyrite separates from the distal Proterozoic country rocks of the Jinchuan deposit have δ^{34}S from 1.93 to 11.23 ‰, and Δ^{33}S values from -0.04 to -0.08 ‰. The pyrites in the country rocks with Δ^{33}S values less than -0.06 ‰ appear to contain recycled Archean sulfur. Our new data clearly indicate the presence of Archean sedimentary sulfur or recycled Archean sedimentary sulfur in the Jinchuan Ni-Cu sulfide deposit, but when and how it was introduced to the deposit remain to be investigated.

NI ISOTOPE VARIATIONS OF THE J-M REEF, STILLWATER COMPLEX, MONTANA

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Sulfide and silicate samples are being analyzed to show the distinction in isotopic composition of nickel in different mineral phases of the J-M Reef. All sulfide samples studied here from within the reef are hosted as disseminated sulfides containing chalcopyrite, pyrrhotite, and pentlandite. Pentlandite is the primary host for nickel in the sulfide minerals, but the samples often contain mostly pyrrhotite with small exsolutions of pentlandite These samples had δ^{60} Ni values which range from -0.02 to -0.22‰ ± 0.05‰ relative to NIST SRM 986. In addition, two secondary standards, USGS reference material Nod-A-1 (four separate aliquots) and an Alfa Aesar Ni ICP solution (3 separate aliquots), were processed and found to be (1.25 ± 0.16‰ and -0.08 ± 0.06‰) respectively, in agreement with previously published values. Previous studies have found that magmatic sulfide deposits typically have isotopically light δ^{60}Ni values with komatiite hosted sulfides ranging from -0.10 to -1.03‰. For comparison, the average mantle Ni isotopic composition is presumed to be 0.23 ± 0.06‰ for the δ^{60}Ni values. The sulfides within the reef vary between each drill core with anorthosite, gabbro, gabbronorite, and troctolite being the primary hosts. There is little isotopic variance observed between the different rock types, but the troctolitic hosted sulfides appear to be slightly isotopically lighter than the others. The average isotopic composition from six troctolite samples yield -0.16 ± 0.08‰ while the anorthosite, gabbro, and gabbronorite samples average was -0.08 ± 0.10‰. This slight difference could be produced because the olivine in the troctolite samples tend to pull out slightly heavier isotopes than orthopyroxene or sulfide minerals. Olivine and orthopyroxene will also be run to see the isotopic variability between the silicate phases present in association with the nickel bearing sulfides.

MAGNETIC SUSCEPTIBILTY OF CONTACT METAMORPHOSED COUNTRY ROCK SEDIMENTS AS AN EXPLORATION TOOL FOR MINERALIZED PERIDOTITE CHONOLITHS: EAGLE AND EAGLE EAST NI-CU-CO-PGE DEPOSITS, UPPER PENINSULA, MICHIGAN

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Surrounding the Mid-Continent Rift-related Eagle and Eagle East peridotite-hosted Ni-Cu-Co-PGE ore bodies there are over 100,000 magnetic susceptibility data points collected from drill core. While performing these measurements on the Proterozoic-aged Baraga Basin country rock sediments, a gradual increase in readings was observed leading up to- and within the visibly distinct, and often very discrete (ranging from 0.5-5 meters in thickness) contact metamorphic halo around the peridotite bodies. This study aims to test if the increase in magnetic susceptibility, related to contact metamorphism, can be extended beyond visible hornfels in order to better target mineralized chonoliths within the sedimentary host-rocks.

The Michigamme Formation of the Baraga Basin is broadly divided into three members: Fossum Creek, Upper Greywacke, and Lower Slate, all of which consist of fine grained pelitic siltstone, shale, and greywacke. The hornfels-facies contact metamorphic halo is characterized by greenish-grey beds due to the presence of fine-grained chlorite +/- white-mica+/- cordierite.

Each member of the Baraga Basin, in addition to the hornfels equivalents, have unique magnetic susceptibility populations. Based on measurements collected approximately every 3 meters using a KT-10 handheld kappameter, a background magnetic susceptibility for each member was derived from the population mean. Three-dimensional numerical modelling of the sediments and hornfels shows that magnetic susceptibility consistently increases toward the peridotite contacts (0.3-1.2 x 10^{-3}SI units above background). In association with massive sulfides, the magnetic susceptibility doubles in magnitude above background, resulting in a halo that can be modeled 50-150 meters outside the Eagle and Eagle East ore bodies (Figure 1).

Due to strong lithologic and stratigraphic trends in this magnetic susceptibility dataset, geostatistical deconstruction was required to illuminate otherwise overlooked anomalous signatures associated with contact metamorphism within and beyond the range of visible hornfels. With case-specific considerations, this technique has the potential to be a cost-effective exploration tool to vector towards mineralized chonoliths within sedimentary country rocks.

NSR: A TOOL FOR EVALUATING NICKEL-COPPER-PGE SULFIDE DEPOSITS, AND FOR FINANCING EXPLORATION

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Nornickel, a major Russian mining company, anticipates a growing global shortage of nickel, led by “the robust appetite of the battery sector”. Because nickel-copper-PGE sulfide deposits are the source of almost all battery nickel, Nornickel’s forecast highlights the need to explore for such deposits.

In nickel-copper-PGE exploration, companies can use “Net Smelter Returns,” or “NSRs,” in two ways: in evaluating a property, and as a basis for financing.

The NSR of a tonne of ore comprises the proceeds from the sale of the mineral concentrates that a mill extracts from that ore, after deducting the costs of transportation of the concentrates, smelting, refining, insurance and marketing.

In evaluating a property, a company should continually bear in mind the potential NSR of its nickel-copper-PGE mineralization. In particular: (a) location: how far to a smelter? (b) standard metallurgical processes are unlikely to recover, to concentrates, the metals contained in very fine-grained minerals; in violarite; and in any oxide, hydroxide, carbonate and silicate minerals; (c) chrysotile, hydrotalcite and other fibrous materials could make an ore impossible to mill; (e) deleterious substances (notably As, Cr, Cl and Mg) in the concentrates could attract heavy penalties at the smelter.

Exploration companies find it increasingly difficult to raise money on the stock market. As a result, royalties based on NSRs have become increasingly important for financing exploration. Nevertheless, because nickel smelting and refining fees are confidential, it is difficult for an outsider to evaluate an NSR royalty on a nickel-copper-PGE deposit. Lawsuits have resulted.

The royalties least likely to attract lawsuits are gross royalties. The contracts underlying a gross smelter royalty should take into account the possible presence of deleterious substances.

CHANGING OUR UNDERSTANDING OF THE COLDWELL COMPLEX IN THE CONTEXT OF THE MCR THROUGH PASSIVE SEISMIC SURVEY, DIAMOND DRILLING AND GEOCHEMISTRY

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The Coldwell Complex (1108-1105 Ma.) is the largest alkaline intrusion in North America and is associated with the early stage of magmatism in the Midcontinent Rift. Historically, three possible configurations for emplacement were proposed, including: a) spherical dome with ring dyke and cone sheets, b) caldera of a large, rift related volcanic center, and c) successive pulses of co-genetic magma into ring dyke structure.

Passive seismic surveys conducted since 2017 at increasingly sophisticated scope and scale, tested the structure of the Coldwell from its margin at the Marathon deposit westward into the complex. The surveys take advantage of the density and p-wave velocity contrast between Archean footwall, syenite, gabbro and oxide melagabbro. Results of phase 2 and 3 show a large sub horizontal, undulating high velocity zone at a depth of between 700 and 900 m immediately west of, and down dip from the Marathon deposit. A concurrent gravity survey confirmed existence of the high-density unit. The passive seismic results were tested by 1 km deep drill holes through the syenite that returned a thick interval of oxide melagabbro (specific gravity 3.4 to 3.7) from 700-900 m that both confirms the source for the high velocity signal and the reliability of the survey. Stratigraphy beneath Center I syenite west of the Marathon deposit is comprised of alternating basalt, gabbro and syenite units. The uppermost syenite is less than 100 to 300 m thick.

The seismic results and drilling beneath syenite in the eastern half of the complex are used to reform our understanding of the origin of the Coldwell. First, there is no evidence for an outer ring dyke structure. Layering at the margin dips inward toward the center of the complex and quickly flattens to sub-horizontal. Second, the complex did not form as a large thick lopolith having basalt roof pendants. The complex more likely formed by intrusion of thin gabbro or syenite sills into a basalt pile. Finally, the sub-horizontal igneous strata, circular shape of the complex, coincident gravity high, and topographic lineament features are most consistent with an origin for the Coldwell as a volcanic caldera.

The origin of igneous rocks in this setting is of significant interest to exploration. The rocks make up a very diverse assemblage of volcanic and intrusive types that were derived from both tholeiitic and alkaline parentage. Correlation between various units has historically been discouraged by the complicated trace elements relationships, and the widely held belief that initial melt compositions have been overprinted by some combination of fractionation, exotic mineral control, assimilation, or hydrothermal alteration. However, synthesis of a large regional trace element data set resulted in correlation of 5 individual alkaline mafic rock units to form a single group referred to here as the Trans Coldwell Group. The Trans Coldwell Group includes Wolf Camp basalt, alkaline gabbro on the Coldwell Peninsula and Geordie Lake gabbro located within the Coldwell, and several mafic dykes located to the west and south east of the Coldwell that cut Archean greenstone terrane. This Group of intrusive and extrusive rocks occurs over a 120 km strike length centered on the Coldwell Complex, and, assuming the dykes were feeders to basalt, indicate a previously unknown group of alkaline basalts associated with the MCR existed along the north shore of Lake Superior. The large sizes and diverse settings for each unit of the Trans Coldwell Group together with the nearly identical trace element characteristics are highly significant observations because they show factors such as contamination (assimilation), mineral control or hydrothermal alteration did not play a role in petrogenesis. Thus, we expect that a dependable petrogenetic model, including mantle source region, can be formulated for at least one major alkaline rock suite in the Coldwell.

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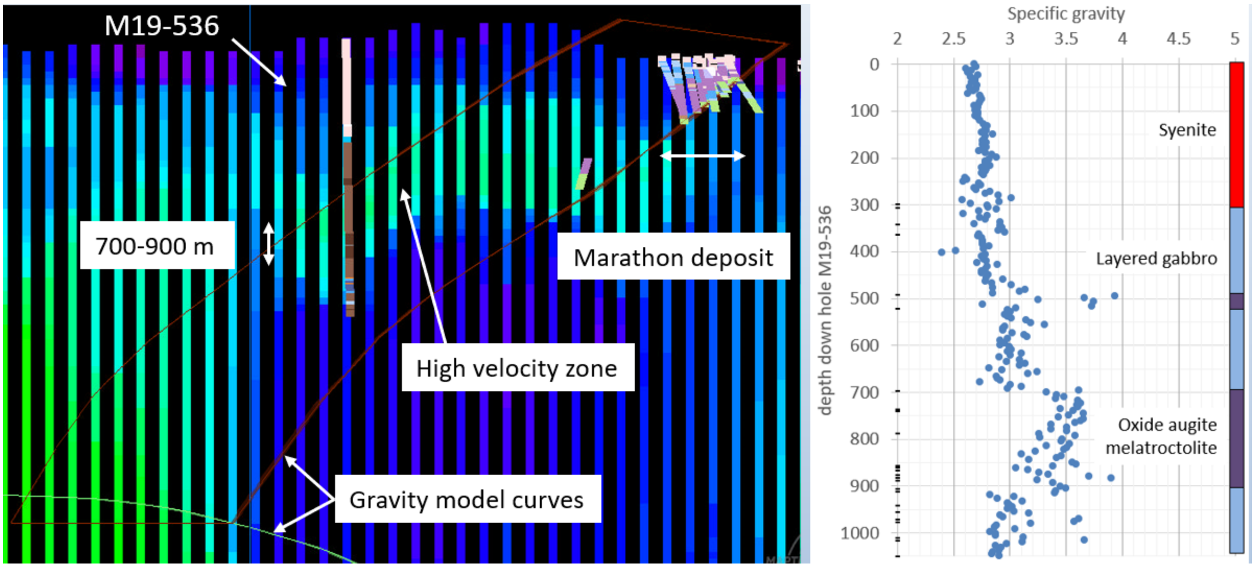

MAGMATIC SULFIDES DID NOT SIMPLY WALK IN TO MORDOR: SO HOW DID THEY GET THERE?

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Magmatic sulfide deposits are generally hosted in mafic-ultramafic complexes that can be considered to be relatively ‘dry’ systems, sourced from moderate to high degrees (10-30%) of mantle melting. Furthermore, they tend to be restricted to plume-related intracratonic layered intrusions, or craton margin conduit settings. The recognition of ‘unconventional’ deposits and occurrences in more alkaline systems, sourced from lower degrees (<10%) of partial melting, is growing. Such occurrences are often linked to post-collisional tectonic settings and are largely recognized at lower-mid crustal depths. This includes intrusions such as the Mordor Alkaline Igneous Complex, Australia, and a number of other lamprophyric-alkaline ultramafic intrusions around the world. Ni-Cu-PGE-Te mineralisation occurs as blebby and semi massive ores. The host rocks contain abundant hydrous silicates and also a strong association with apatite and carbonates. Invariably, these magmas are sourced from significantly metasomatized lithospheric mantle which provides a particular ‘DNA’ to the resultant magmatism, that characteristically contains, tellurides, apatite and carbonate along with the Ni-Cu-PGE sulfides. The carbonate is particularly significant as it may represent a mechanism for propelling otherwise dense sulfides up into the crust, particularly at lower crustal depths. Here mantle-derived carbonate would be present as a supercritical CO_2 fluid, which may aid buoyancy and act as a driver to propel sulfides from the mantle up into and through the crust. However, although it plays a role as an initial propellant, S and C decouple at shallower levels, due to the pressure-dependent solubility of volatiles in silicate melts, effectively erasing any evidence about this important process. Thus, within these unconventional alkaline- mafic-ultramafic systems, C may act like fuel tanks that initiate a rocket launch (here sulfide) but detach once spent before the rocket reaches space.

EMPLACEMENT HISTORY OF THE NEOARCHEAN Cr-Ni-BEARING ESKER INTRUSIVE COMPLEX, RING OF FIRE INTRUSIVE SUITE, NORTH-CENTRAL SUPERIOR PROVINCE, ONTARIO, CANADA: INSIGHTS FROM U- Pb ZIRCON GEOCHRONOLOGY

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One of the most prominent geological features of the north-central Superior Province in Canada is the Ring of Fire Intrusive Suite (RoFIS) which represents the products of a major mafic-ultramafic igneous event and is exposed over ~200km of strike length in the arcuate shaped, Meso- to Neoarchean McFaulds Lake greenstone belt. The RoFIS is subdivided into two main magmatic Subsuites: 1) a spatially restricted ultramafic-dominated Koper Lake Subsuite that hosts world-class Cr and significant Ni-Cu-PGE mineralization and 2) a more widespread mafic-dominated Ekwan River subsuite that hosts numerous Fe-Ti-V prospects, all emplaced within a ~3 my interval between 2735.5 and 2732.6 Ma. The most Cr and Ni-Cu-PGE endowed part of the RoFIS is the Esker Intrusive Complex (EIC), which comprises the Black Thor (BTI) and Double Eagle (DEI) intrusions. The EIC represents flow-through ultramafic-dominated feeder sills where the lower ultramafic parts were produced by repeated influxes of komatiitic magmas accompanied by crystallization of Ol±Opx±Chr-rich cumulates and fractionation of the residual liquid, resulting in a layered stratigraphy comprising interlayered dunites/harzburgites, harzburgites/websterites/chromitites, and websterites/gabbros. After initial emplacement but before complete crystallization, a cogenetic Late Websterite Phase (LWP) reactivated the feeder conduit and transected the lower parts of the BTI. Zircon U–Pb TIMS data indicate that the BTI crystallized over a ~2 my interval between 2735.5 Ma (Mafic Zone) and 2733.6 Ma (LWP). The ages, combined with field observations, reveal that the intrusion was not constructed in a simple, strictly sequential stratigraphic order from the base (oldest) to the top (youngest), but that it exhibits a more complex organization. The BTI and the DEI are interpreted to have initially intruded separately, but to have coalesced over time with magma inflation within a dynamic komatiitic system to form the Cr and Ni-Cu-PGE-bearing EIC, one of the most important members of an increasingly important class of polymetallic magmatic ore systems.

COMPOSITION OF THE J-M REEF MINERALIZATION, STILLWATER COMPLEX, MONTANA, USA

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Order of magnitude variations in the platinum-group element (PGE) tenors in J-M Reef mineralized sulfides have been documented in the areas of the Stillwater Mine and East Boulder Mine in the Stillwater Complex layered mafic intrusion. We present whole-rock data (Ni, Cu, Pd, Pt ± S) collected over 20 years of mining. Estimated sulfide tenors across both mines show both localized and deposit-wide variations.

Local variations in sulfide tenor can be explained by fractionation of sulfide liquid within reef mineralization resulting in domains with elevated Cu, Pt, and Pd relative to other samples collected within the same drill hole. Deposit wide tenor variations were examined using Empirical Bayesian kriging to calculate predicted value surfaces for the sulfides in the Stillwater Mine area. Furthermore, assays from the Stillwater Mine were grouped into mine blocks based on geology and/or mine convention.

Statistically significant variability is observed between the various mine blocks that demonstrates, despite local variation in tenors, overall regional scale processes have also heterogeneously enriched the J-M Reef sulfides. This variability is best explained by the ratio of silicate liquid to sulfide liquid in the primary magmatic system from which the sulfides exsolved (i.e. an R factor effect). Secondary magmatic and post-magmatic processes may have modified the composition of the sulfides and complicated our ability to estimate the primary composition of the sulfide liquid. The removal of sulfur from the mineralized reef rocks, either by dissolution of the primary sulfide liquid by a S-undersaturated magma or subsolidus hydrothermal processes, will lead to an overestimation in the tenor of the sulfides by underestimating the amount of S contained in the primary sulfide liquid. The nugget effect of sampling one very large platinum group mineral (PGM) will similarly lead to overestimations in sulfide metal tenors. This work shows that variation in grade across the Stillwater Mine is not entirely accounted for by the amount of sulfide mineralization present in one part of the reef to another, but also due to the composition of the sulfides themselves.

SULFIDE-SILICATE TEXTURAL RELATIONSHIP IN DISSEMINATED Ni-Cu-PGE MINERALIZATION OF MOLOPO FARMS COMPLEX, TUBANE AREA, SOUTHERN BOTSWANA

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The Molopo Farms Complex mafic-ultramafic layered intrusion is located towards the western margin of the Archean Kaapvaal Craton, southern Botswana. Based on a combination of drill core observations, petrography and whole-rock geochemistry we present the various preserved textures and discuss the implications for their genesis. The sulfides commonly occur as fine disseminated grains sporadically distributed within the host rocks. Locally, sulfide globules and poikilitic net textured sulfides are preserved. The globular textured sulfides up to one centimetre in size are sparsely distributed in the host rocks, locally showing ragged grain margins with an alteration haloe now occupied by secondary silicates and magnetite. The poikilitic net textured sulfides are characterised by interconnected networks at millimetre to centimetre scales, enclosing euhedral and subhedral orthopyroxene and plagioclase grains. This texture is ascribed to percolation of sulfide melt through partially crystallized silicate melt. Sulfide minerals are dominated by pyrrhotite, with minor pentlandite and chalcopyrite constituting less than 3 modal % of the rock mostly interstitial to cumulate orthopyroxene. Platinum group minerals are found at the edges of sulfide mine

rals, and occur as discrete grains within the altered silicates around the sulfides consistent with a magmatic origin. Notably, the concentration of Pt and Pd are higher compared to other PGEs with values reaching up to 179 ppb and 203 ppb respectively. The high Pt and Pd contents are manifested by the occurrence of Pt-Pd bismuthotellurides and sperrylite. It is proposed and that the local presence of up to a centimetre sized sulfide globules indicates that the host magmas were capable of segregating massive sulfide accumulations. Sulfide saturation likely occurred in response to assimilation of external sulfur either from the pyrite-bearing host sedimentary sequence or other sulfur sources at depth.

GENESIS OF Ni-Cu-PGE MINERALIZATION IN THE SUDBURY IGNEOUS COMPLEX: IMPACT DEVOLATILIZATION, THERMOMECHANICAL EROSION, AND DYNAMIC UPGRADING OF SULFIDE XENOMELTS

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Most magmatic Ni-Cu-PGE deposits form from mantle-derived mafic-ultramafic magmas, are hosted by lava/magma conduits, and occur preferentially in rift-related tectonic settings. However, the Ni-Cu-PGE mineralization in the 1850 Ma Sudbury Igneous Complex – one of the largest accumulations of magmatic Ni-Cu-PGE mineralization on Earth – formed from a crustal impact melt and is hosted by norites, quartz diorites, and associated magmatic and impact breccias. Most models involve exsolution of immiscible sulfides during cooling of the impact melt, gravitational settling to the basal contact, and sweeping into topographic embayments by convection currents or as gravity flows followed by local injection into radial and concentric “offset” dikes and footwall rocks. Variations in the S-Os-Pb isotopic compositions of the ores around the SIC have been explained by incomplete mixing or local “interaction” with underlying rocks, but this cannot explain the magnitudes of the variations, the insignificant variations in Hf isotopic compositions of overlying silicate rocks, or the mismatch between observed ore tenors and metal depletion trends in overlying norites. The wide variations in Pb isotopic variations have been attributed to volatilization of Pb from the impact melt followed by incorporation of Pb from underlying rocks, but S is as volatile as Pb, so it should have been also devolatilized. This leads to an alternative model for ore genesis involving 1) syn-impact devolatilization of significant amounts of Hg-Tl-Cd-S-Se-Sn-Te-Zn-Pb-Bi and lesser amounts of Sb-Ag-Cu-Au-As from the impact melt, 2) mechanical and convective homogenization of all chalcophile (S-Fe-Ni-Cu-Pt-Os-Pb) and lithophile (Sr-Nd-Hf) isotopic systems during formation of the impact melt sheet, and 3) significant local thermomechanical erosion and incorporation of barren Fe sulfides (Huronian basalts/sediments), subeconomic Fe-Cu-Ni-(PGE) sulfides (most Nipissing and/or East Bull Lake Intrusive Suites), or economic Fe-Ni-Cu-(PGE) sulfides (Shakespeare-type Nipissing intrusives), forming sulfide xenomelts that reacted with overlying impact melt to produce the observed variations in Ni-Cu-PGE tenors and S-Pt-Os-Pb isotopic compositions.

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STRUCTURE AND EMPLACEMENT OF THE EAGLE PERIDOTITES AND THEIR ASSOCIATED NI-SULFIDE MINERALIZATION, MICHIGAN, USA

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We present results of a structural analysis of the ca. 1107 Ma Eagle peridotites and associated Eagle and Eagle East Ni-sulfide ore bodies based on structural measurements in oriented drill core and three-dimensional (3D) modeling of a borehole dataset provided by Lundin Mining Ltd. The Eagle peridotite comprises two EW-trending, generally blade-shaped dykes with complex geometries in long and cross section. The peridotite bodies intruded weakly to moderately deformed, ca. 1.85 Ga Baraga basin sandstones and shales that contain open, north-verging, subhorizontal E-W plunging folds with a variably developed moderately south dipping axial plane cleavage. The western Eagle peridotite is a ~400 m long, 100-200 m wide dyke in map view with a ~300 m deep trough-shape profile in long section. This peridotite body is associated with marginal igneous breccias with clasts of fine-grained gabbro and pyroxenite, interpreted to be a collapsed early marginal facies. Sulfide mineralization occurs at the base of the trough and it also extends into the host rocks parallel to bedding. The Eagle East peridotite is a ~1500 m long dyke-like body in plan view that extends to ~1200 m depth, with a much more complex shape in long section, in which transitions in geometry occur across changes in the host rock lithology. The upper part flairs upwards in long section with a ~45° east-dipping western edge and a subvertical eastern edge. This part of the intrusion transitions into a very gently west-plunging, flattened chonolith at about 1000 m, which extends ~700 m east to a younger, vertical plug-like gabbro occupying the inferred feeder of the Eagle system. The chonolith hosts the ~300 m long, tubular Eagle East ore body, which also extends out into the host rocks, parallel to bedding. Unlike Eagle, the Eagle East intrusion is associated with peridotite- and sulfide-hornfels breccias, inferred to have formed during or prior to emplacement of the main magma phase. We propose that Eagle East was a complex feeder to a now eroded laterally E-W propagating, vertical, blade-shaped dyke. In this context, the Eagle peridotite formed as an undulation at the base of the dyke, deepened by thermal-mechanical erosion. Sulfide liquids migrated downwards in the system and were trapped at the base of Eagle and within the sub-horizontal chonolith deep in Eagle East.

EXPLORATION AND DISCOVERY OF THE EAGLE AND EAGLE EAST NI-CU-CO-PGE DEPOSITS, UPPER PENINSULA, MICHIGAN

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The Yellow Dog Peridotite (YDP), a little known, isolated outcrop in the Upper Peninsula of Michigan, was the subject of two studies in the 1970's. In the early 1990's Kennecott Exploration (KEX) conducted regional mapping and prospecting in the Baraga Basin and discovered abundant glacial Ni-Cu bearing rocks in a gravel pit east of L'Anse. Exploration for magmatic-hosted deposits ensued and in 1995 KEX drilled the YDP with little encouragement. In 2001 KEX (now acquired by Rio Tinto) returned and again tested the YDP as well as a similar, separate airborne magnetic anomaly corresponding to a much smaller outcrop of peridotite in 2002. The Eagle discovery hole consisted of 84.2 meters of 6.3% Ni and 4.0% Cu. At the time of permitting, the inferred resource consisted of 3.51 MT grading 3.72% Ni and 2.95% Cu with an additional 0.54 MT of inferred. Extensive drilling of the original YDP, now known as Eagle East, identified significant volumes of uneconomic, mostly disseminated nickel copper mineralization. Mine construction began in 2010 and in 2013 Lundin Mining Corp. acquired the project from Rio Tinto. Production began in late 2014, when by that time, the resource had been increased through additional drilling to 4.83 MT indicated at 3.52% Ni, 2.94 % Cu, 0.75 g/t Pt, 0.51 g/t Pd, 0.29 g/t Au and 0.10% Co. Lundin reinvigorated exploration efforts to discover additional mineralization that could be accessed through the planned Eagle Mine development area. Previous efforts to define a traceable conduit to the Eagle deposit were unsuccessful. Nor was a physical link to Eagle East identified. The remaining option for a potential source conduit was the deep extension of Eagle East, which had not been previously tested. The Eagle exploration team shifted focus to trace the deep Eagle East dike using Devico directional drilling to drill a series of kick-offs from a single parent hole. Each successive kick-off drilling deeper than the previous. Drilling started in late 2013. In 2014 the drilling was encouraged by intercepts of magmatic breccia and heavy disseminated mineralization bordering on semi-massive sulphide. In the winter of 2015, the first hint of massive sulphide was intersected. In June 2015, Lundin announced the Eagle East discovery holes with intersects of 30.85 meters at 5.23% Ni and 8.74% Cu and 23.85 meters at 5.34% Ni and 4.41% Cu. The Eagle exploration team had developed and honed an innovative use of Devico drilling to the point that up to 15 kick offs were obtained from one parent hole. In June 2016 Lundin published a maiden resource of 1.18 MT of 5.2% Ni and 4.3% Cu that was the result of over 80 drill intercepts from only ten parent holes. After three years of development, Eagle East went into production in late 2019, and extended the LOM by 1.5 years to Q3 2025.

FORMATION OF THE FLATREEF DEPOSIT, NORTHERN BUSHVELD, BY HYDRODYNAMIC AND HYDROMAGMATIC PROCESSES

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The growing body of information from the Flatreef suggests that the deposit formed through a combination of magmatic, hydrodynamic and hydromagmatic processes. (i) Influx of several batches of PGE fertile basaltic magma. The magmas became saturated in an immiscible sulphide melt due to assimilation of country rock sulfides during emplacement resulting in higher Cu contents than in the remainder of the Bushveld. Assimilation was particularly pronounced in the initial magma batches from which the lower portion of the Flatreef crystallised. We do not subscribe to the model of entrainment of PGE-rich sulfides from a staging chamber, mainly because the fine grained marginal rocks to the intrusion are sulphide undersaturated. (ii) Deposition of a thick pile of mafic-ultramafic cumulates caused subsidence of the magma chamber. Aided by flux of volatiles from the cooling cumulates and the devolatising country rocks, subsidence and associated seismicity facilitated slumping of crystal slurries located at the top of the growing cumulate pile towards the centre of the Bushveld lopolith and into local troughs. This resulted in sorting and compaction of the slurries, pronounced layering and localised hydrodynamic erosion of floor cumulates. (iii) Contacts between compositionally and texturally distinct layers acted as traps for volatiles that ascended through the cumulate pile triggering partial melting and recrystallization of cumulates to form pegmatoidal rocks that may be highly enriched in sulfides, secondary olivine and, in some cases, graphite and phlogopite. (iv) The volatiles mobilised Pd from the interior of the intrusion towards its margin, leading to relatively low Pt/Pd and high Pd/Ir ratios in much of the Flatreef. (v) The partial melting of the Flatreef cumulates facilitated downward percolation of sulfides, locally for up to several 10s of metres. In places, ultramafic cumulates injected into their fluidised, volatile-rich footwall rocks forming extensive sill-like apophyses. The combination of these processes resulted in pervasively recrystallized cumulate packages hosting exceptionally thick PGE mineralised intervals (up to more than 300 m at > 1ppm PGE).

MODELLING OF THE DISTRIBUTION OF TE, AS, BI, SB, SN (TABS) AND SE IN THE MERENSKY REEF AND THE IMPLICATION FOR PGE COLLECTION MECHANISMS IN MAGMATIC SULFIDE DEPOSITS

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Two main models have been proposed to explain the collection of platinum-group elements (PGE) from silicate liquid by an immiscible sulfide liquid. In the first model, the distribution of PGE is chemically controlled by their very high partition coefficients into an immiscible sulfide liquid. Alternatively, it has been proposed that PGE self-organize as nanometer size clusters in the sulfide liquid, which could be captured by an immiscible sulfide liquid. The main difference between both models is that in the cluster model the distribution of PGE would be physically controlled by the surface properties of nanometer-sized particles. Consequently, the partition coefficients of PGE, and other cluster-forming elements, would not affect their distribution in the cluster model. A way of testing which mechanism is more appropriate is to model the expected distribution of chalcophile elements with different partition coefficients in a sulfide deposit, and then compare with measured values. If the cluster model is valid, the distribution of the elements should not be controlled by their partition coefficients. We have measured the concentrations of Te, As, Bi, Sb (TABS), Se and PGE in the parental magmas from which the Bushveld Complex have formed (Marginal Zone), and used the results to model the composition of the Merensky Reef. The components of the reef have been modelled as cumulate sulfide liquid, silicate liquid and cumulate (silicate minerals and oxides). The cumulate sulfide liquid was calculated using the zone refining equation and taking into account the different partition coefficients of PGE, Se and TABS between silicate and sulfide liquids, and an N factor of 20,000. The modeled concentrations closely resemble the measured values obtained for a section across the Merensky Reef at the Impala mine. The modeling also reveals that the distributions of PGE, Se, Te and Bi in the reef are essentially controlled by the presence of sulfide minerals, whereas As and Sb distributions are controlled by both sulfide minerals and melt component. This is because PGE, Se, Te and Bi are moderately to highly chalcophile elements, whereas As and Sb are only slightly chalcophile elements. Therefore, our results support the model of distribution of PGE, Se and TABS controlled by their different chalcophile nature, and do not favor their distribution to be physically controlled as suggested by the cluster model.

Keywords - Te, As, Bi, Sb, Sn; platinum-group elements; magmatic sulfide deposits; Bushveld Complex; platinum-group minerals

TRACE ELEMENTS IN PYRRHOTITE, PENTLANDTE, CHALCOPYRITE AND PYRITE FROM MAGMATIC SULFIDE DEPOSITS: AN OVERVIEW

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Over the past two decades the distribution of trace elements in base-metal sulfides (BMS) from magmatic sulfide deposits (i.e. Ni-Cu-PGE and PGE-dominated deposits) has been extensively investigated, and much information is now available. We have compiled the trace-element concentrations in BMS, obtained by LA-ICP-MS, from various magmatic sulfide deposits to understand whether they may record the ore forming processes. Among the samples, there are some of the most studied Ni-Cu-PGE (e.g. Aguablanca, Duluth, Jinchuan, Noril'sk-Talnakh, Sudbury, Voisey's Bay and others), and PGE-dominated (e.g. Bushveld, Lac des Iles, Stillwater, Great Dyke and Penikat) deposits of the world. The results reveal that it is possible to separate BMS from Ni-Cu-PGE and PGE-dominated deposits based on the concentrations of highly chalcophile elements. For instance, pentlandite from Ni-Cu-PGE deposits has much lower Rh and Pd concentrations than those from PGE-dominated deposits. This is because of the higher R-factors in PGE-dominated deposits relative to Ni-Cu deposits, and consequently greater concentrations of these elements in the sulfide liquid. The BMS also record the fractional crystallization of the sulfide liquid. The concentrations of elements compatible with MSS and ISS are lower in BMS from more fractionated ores, whereas concentrations of incompatible elements increase in BMS from progressively more fractionated ores. Also, since both Se and Te behave as incompatible elements during crystallization of the sulfide liquid, but Te is more incompatible than Se, the Se/Te ratio in BMS decreases with progressive fractionation, and can also be used to track the differentiation of the sulfide liquid. Crustal assimilation by the parental silicate liquids can also be constrained using the concentration of slightly chalcophile elements in BMS. This is because high R-factors do not obscure the effect of crustal contamination for elements with low partition coefficients between sulfide and silicate liquids. We propose that a plot of As/Se vs Sb/Se in pentlandite may be appropriate for assessing crustal contamination. The pentlandite from ores that formed from more contaminated silicate liquids have higher As/Se and Sb/Se ratios. Finally, the composition of pyrite may be used to investigate the late- or post-magmatic alteration of BMS. Magmatic pyrite have higher Co/Se and Sb/As ratios relative to pyrite formed in other settings, which could be useful for the use of pyrite as an indicator mineral.

EARLY HYDROTHERMAL MODIFICATION OF THE AURORA AND WATERBERG PTM MAGMATIC SULPHIDE NI-CU-PGE DEPOSITS IN THE NORTHERN BUSHVELD COMPLEX, SOUTH AFRICA

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The role of volatiles in the development of layered intrusion hosted magmatic sulphide deposits is still poorly understood. We present petrological and fluid inclusion evidence of early hydrothermal remobilisation of platinum-group elements (PGE) in two deposits (Aurora and Waterberg PTM) from the northern Bushveld Complex where magmatic sulphide Ni-Cu-PGE deposits are hosted in leucocratic rocks of the Main Zone and the Upper Zone. Aurora is possibly an extension of the Waterberg system, however Aurora contains dolomite country rock xenoliths which are very rare at Waterberg. PGE in the Aurora project and the T zone at Waterberg are hosted in Pd-Te-Bi platinum group minerals (PGM) which are spatially removed from magmatic sulphides and hosted in silicates; suggestive that the PGE in these deposits have been remobilised by hydrothermal processes.

Fluid inclusions were identified in cumulate magmatic silicates (olivine, pyroxene and feldspar) in both deposits. These inclusions comprise brine, vapour and rare salt melt inclusions which do not crosscut crystal boundaries and terminate against peritectic reaction rims. Optical microscopy and raman spectroscopy has shown the brine inclusions in Aurora and Waterberg are highly saline (60 – 80 wt.% NaCl equiv.), contain multiple daughter minerals (including halite, sylvite, calcite and magnesite) and a small amount of liquid H_2O. The vapour inclusions contain CH_4 and N_2. Microthermometry shows the Aurora inclusions have minimum trapping temperatures of 820 – 920°C, meaning the trapped fluids were present while the system was at least partially molten. We propose that these early hydrothermal fluids remobilised PGE from a molten Cu-sulfide (iss) phase to form PGM away from the sulphides. Microthermometry data will be presented for inclusions from the Waterberg PTM deposit to reveal if similar processes occurred there.

The petrological similarity between inclusions in the Aurora and Waterberg T zone deposits suggests the hydrothermal fluids had a similar origin, either from late magmatic degassing or possibly from assimilated dolomite country rock. This has important implications for geometallurgy in northern Bushveld Ni-Cu-PGE deposits, and in layered intrusion hosted deposits more generally.

LITHOSTRATIGRAPHY, MINERALIZATION, AND PETROGENESIS OF THE MCR-RELATED SUNDAY LAKE INTRUSION, NW ONTARIO

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The Sunday Lake Intrusion (SLI), situated ~ 30 km north of Thunder Bay, Ontario, is a small, funnel-shaped, well differentiated ultramafic-mafic layered intrusion emplaced into Archean metasedimentary rocks during the early magmatic stage of the 1.1 Ga Midcontinent Rift. Building on the earlier work of Flank, (2017), this talk reports on the lithostratigraphy, mineralization, and interpreted petrogenesis of the SLI based on petrographic and geochemical studies of 37 samples from two drill core that completely profile the intrusion.

Petrographic and geochemical data from the two drill core show that the SLI can be subdivided into four main lithostratigraphic zones based largely on their cumulus mineralogy. Upsection, the main subdivisions are 1) the non-cumulate and well-mineralized **Basal Mineralized Zone**, 2) the **Lower Ultramafic Zone** composed of Ol cumulates, 3) the **Upper Ultramafic Zone** dominated by Ol+Cpx cumulates, and 4) the **Gabbro Zone** composed of Pl+Cpx+Ox cumulates.

In addition to the significant Cu, Ni and PGE mineralization occurring in the Basal Mineralized Zone, several other mineralized intervals occur in the SLI. The most distinctive is Cu-PGE reef-style mineralization that occurs over an 80-130 meter interval straddling the contact between the UUZ and the GZ in both drill core. As is commonly observed in other orthomagmatic reefs generated by fractional crystallization-induced sulfide saturation (e.g., Skaergaard, Sonju Lake), PGE and Cu peaks are offset. Other narrow (<8m) intervals of elevated Cu-Ni-PGE concentrations occur in the UUZ.

The stratigraphic sequence of cumulus mineral arrivals in the Sunday Lake intrusion is:

Ol(+CrSp) → Ol+Cpx → Pl+Cpx+Ol → Pl+Cpx+Ox → Pl+Cpx+Ox+Ap (+Gp).

Such a crystallization sequence is common among the mineralized early ultramafic-mafic intrusions of the Midcontinent Rift (e.g., Eagle, Tamarack, Seagull) and implies crystallization from a high-Mg, low-Al tholeiitic magma. This unidirectional progression of cumulus minerals and generally smooth chemostratigraphic trends of increasing IE abundance and decreasing mg#, suggest that the SLI formed by bottom-up fractional crystallization driving magmatic differentiation in a largely closed system. However, there are indications, based on abrupt increase in mg#, Cu and PGE and lithologic complexities, that the SLI was open to one or more recharge events during formation of the LUZ and UUZ.

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GEOLOGY, MINERAL DEPOSITS, AND TECTONOMAGMATIC EVOLUTION OF THE MIDCONTINENT RIFT IN THE LAKE SUPERIOR REGION

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For over a century, many geologic, geochemical, geochronologic, and geophysical studies have been focused on the Mesoproterozoic (1.1 Ga) volcanic, intrusive, and sedimentary rocks that compose the Midcontinent Rift (MCR) in the Lake Superior region. In the past quarter century, in particular, the empirical data collected from such studies have vastly improved our understanding of the three-dimensional structure and tectono-magmatic evolution of the MCR. These studies have shown the Midcontinent Rift to be one the best preserved large igneous provinces of Precambrian age and one of the most metallogenically prospective.

While new high-resolution age dates continue refine the details, it has been fairly well established for the past couple decades that the tectonomagmatic evolution of the rift progressed over a span of 25 to 30 million years in several distinct stages.

Initiation Stage (1115-1110 Ma) – Some of the oldest dates ascribed to the MCR fall in this age range and come from several mafic and ultramafic intrusions in NW Ontario. A couple of these dikes have been re-dated and yield younger (<1110 Ma) ages. If the remaining older ages are valid, the lack of volcanics of this age might be explained as resulting from crustal doming over a mantle plume causing their erosion.

Early Stage (1110-1105 Ma) - This stage is represented by reversed polarity lavas and intrusions of diverse compositions (ultramafic to felsic). All reversed volcanic sequences show similar chemostratigraphy where early primitive basalts (mg#>50) give way to more diverse compositions that show evidence of crustal contamination. Rhyolites with distinctly negative δ_{Nd} values, thought to indicate crustal anatexis of Archean to Paleoproterozoic crust, also begin to appear later in this early stage of volcanic activity. Many small, well-mineralized ultramafic-mafic intrusions (e.g., Eagle, Tamarack, Sunday Lake, …) and dike and sill swarms were emplaced during this stage, as was the alkaline Coldwell Complex and early gabbros and granites of the Duluth Complex.

Hiatus Stage (1105-1101 Ma) – This stage is characterized by a cessation of mafic magmatism and only intermittent felsic magmatism in the upper crust. It is thought to represents a period of extensive magmatic underplating of the crust that is implied by geophysical models. Initial ponding of mafic magmas at the Moho is thought to have caused lower crustal anatexis causing more mafic ponding and triggering more crustal melting and ultimately preventing mafic magmas from passing through the crust for about 4 million years. This interruption in mafic magmatism may also have been caused by a waning of extensional tectonics over this period.

Main Stage (1101-1093 Ma) – The bulk of preserved volcanic and intrusive rocks filling the MCR were emplaced during this stage, which occurred during a period of normal polarity. Although the magmatism involved a variety of magma compositions from primitive basalts to rhyolites as in the early stage magmatism, the mafic and minor intermediate compositions of the main stage show little evidence of crustal contamination. The major subvolcanic intrusive complexes, including the extensive Cu-PGE mineralization of components of the Duluth Complex, were emplaced at this time in several major pulses - Mellen at 1101-1100Ma; Duluth at 1099-1098 Ma (Duluth Complex), and Beaver Bay/Crystal Bay at 1096-1093Ma.

Late Stage (1093-1083 Ma) – This stage is characterized by intermittent and localized volcanic activity in a period otherwise dominated by deposition of immature detrital sediments. These eruptions include a range of magma compositions from mafic to intermediate to felsic. Intrusions younger than 1093Ma are rare and typically occur as dikes. Although no upper crustal magmatism evidently occurred after 1083 Ma, migration of copper-bearing crustal fluids occurred along reversed faults as late as 1040 Ma and locally resulted in the deposition of native copper and silver within the upper reaches of the volcanic pile.

CHARACTERIZATION AND FORMATION OF CONTACT-TYPE Ni-Cu-PGE MINERALIZATION IN THE NORTH RANGE OF THE SUDBURY IGNEOUS COMPLEX, ONTARIO*

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The Sudbury Igneous Complex (SIC) hosts some of the world's largest Ni-Cu-PGE sulfide deposits. The ores occur primarily within magmatic breccias and brecciated footwall rocks along the basal contact of the structure or in radial and concentric offset dykes that extend into underlying footwall lithologies. Despite 135 years of research the exact mechanisms of ore formation are still debated. Most current models involve the exsolution of immiscible sulfides from the impact melt sheet, followed by gravitational settling and sweeping into topographic embayments at the base by convective currents. However, this process cannot account for the strongly heterogeneous Pb-S-Os isotopic composition of the ores or discrepancies between observed metal tenors and metal depletion trends in the overlying igneous rocks. The aim of this project is to better understand the parameters responsible for the generation of contact-type Ni-Cu-PGE mineralization on the North Range of the SIC, large segments of which are well exposed on surface and in abundant diamond drill cores. We are testing an alternative model that includes 1) syn-impact devolatilization of S, Pb and other volatile elements from the impact melt, 2) post-impact thermomechanical erosion of footwall rocks to form embayments and troughs and to assimilate S from underlying footwall rocks and 3) formation of local sulfide and inclusion-rich xenomelts that continued to interact with the overlying melt sheet. Detailed sampling of drill core and outcrop sections through the Main Mass of the SIC on the North Range will help constrain metal mass balances in order to better understand the metal depletion and sulfide saturation history of the SIC. Detailed geological, petrographic and geochemical studies of Sublayer and Footwall Breccia will aid in determining their relationship to the sulfide mineralization and the mode and extent of thermomechanical erosion in forming ore-localizing footwall embayments, as well as in creating sulfide-inclusion-rich xenomelts at the base of the SIC. Ultimately, a better understanding of the processes involved in the formation of the sulfide ores associated with the SIC will help to define better constrained vectors to mineralization, which will aid in discovering new deposits.

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STRUCTURAL AND LITHOLOGICAL CONTROLS ON THE EMPLACEMENT OF THE NOVA-BOLLINGER DEPOSIT, ALBANY FRASER OROGEN, WESTERN AUSTRALIA

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The Nova-Bollinger Ni-Cu-Co sulfide deposit is hosted within the 1.3Ga Fraser Zone of the 1.8-1.1Ga Albany Fraser Orogen, located in the south-east of Western Australia. The deposit contained a pre-mining resource of 14.6Mt @ 2.2% Ni, 0.9% Cu and 0.08% Co. This study aimed to define the emplacement controls of the deposit in order to develop a set of exploration targeting criteria and is built upon the relogging of 66 diamond holes, underground mapping, 3D modelling and petrographic analysis.

The Nova-Bollinger sulfide mineralization is associated with a mafic-ultramafic intrusive complex emplaced into granulite facies country rocks. The intrusive complex is grouped into an upper intrusion a lower intrusion and are linked by a thin sill-like intrusion. The intrusions are composed of norite, gabbronorite, websterite, olivine websterite and lherzolite. The country rock sequence comprises siliciclastic metasediments, marbles, conglomerates, mafic granulites, granitic orthogneiss and iron formations. The intrusive complex has been emplaced at the boundary between a sequence dominated by mafic granulite and granitic gneiss and a sequence dominated by siliciclastics, marbles and iron-formation. The contrasting rheology of the sequence boundary is inferred to be a key focusing mechanism for intrusion emplacement.

The country rocks of the project are strongly deformed with up to four phases of folding recorded. Gneissic layering (S_1) and a gentle to moderately NE-plunging sillimanite mineral lineation are the dominant fabrics preserved. F_2 folds affecting the gneissic foliation are dominated by NW-verging, S-folds that plunge 25-40°→040-050°, subparallel to the sillimanite mineral lineation. The gneissic foliation and F_2 folds were reworked by NE-trending F_3 folds and NW-trending F_4 folds. This fold combination created Type-1 fold interference patterns expressed as 'eye' shaped geometries evident in aeromagnetic imagery. Fold orientation and geometry played a key role in the emplacement of the intrusive complex with the individual intrusions aligned parallel with the plunge of the fold axes and mineral lineations.

IGO acquired 3D seismic data over the Project in 2018. The 3D data can be used to map the controlling fold architecture and rheological stratigraphic boundaries allowing the exploration team to drill blind extensions of the intrusive complex throughout the project.

NEW POTENTIAL INDICATOR MINERALS FOR MAGMATIC SULFIDE MINERALISATION

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Small conduit or chonolith style intrusions dominated by olivine- and pyroxene-rich cumulates are well known to be favourable hosts to magmatic Ni-Cu-(PGE) sulfide mineralization. The pyroxenes within many of these economically mineralized intrusions show complex zoning in Cr that can take the form of; 1) abrupt zoning 2) sector zoning and/or 3) oscillatory zoning and any combination of the three types.

We use microbeam XRF element mapping to image Cr in cumulus and poikilitic pyroxenes from variably mineralized mafic-ultramafic intrusions in the Kotalahti Ni-belt, Finland; Ntaka Hill, Tanzania; Noril'sk-Talnakh, Siberia; Aguablanca, Spain; Huangshanxi (Central Asian Orogenic Belt), NW China; Xiarihamu, Tibet; Nova-Bollinger, Australia; and Savannah, Australia.

The mineralized bodies display complex Cr zonation in both the clinopyroxene and orthopyroxene. The pyroxenes investigated from un-mineralised intrusions show only continuous normal zoning. We suggest that the complex zonation features, particularly where observed in orthopyroxene with olivine and spinel inclusions, are indicative of dynamic assimilation of conduit wall rocks accompanied by rapid, disequilibrium fluctuations in silica content and redox state. These processes are strongly associated with Ni-Cu sulfide ore formation in magmatic conduit systems.

Chromium zonation patterns are easily observable using desktop XRF mapping units and can also be visible in thin section or SEM in the case of high-P pyroxenes that have exsolved spinel lamellae. Hence it has a simple application in exploration as an *in-situ* prospectivity indicator for Ni-Cu-Co sulfide mineralized intrusions.

MODELS AND PROCESSES OF OFFSET DIKE FORMATION IN THE SUDBURY IGNEOUS COMPLEX*

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Radial and concentric offset dikes intruded from the Sudbury Igneous Complex (SIC) into the footwall rocks contain ~50% of the total ore reserves and resources in the SIC. Their margins are interpreted to represent the initial impact melt composition modified by variable amounts of contamination by their wall rocks. Thus, they play an important part in understanding the formation of the SIC and represent highly prospective exploration targets. Despite the fact that some of these dikes have been studied in great detail and have been mined for over 130 years, their genesis is still debated. Two end-member models have been proposed for their emplacement: 1) multi-stage injection of an initial phase of sulfide-poor, inclusion-poor quartz diorite melt (QD) followed by a second phase of sulfide-rich, inclusion-rich quartz diorite melt (MIQD) in the center of the dikes, and 2) single-stage injection of MIQD melt with flowage differentiation producing marginal QD and interior MIQD. Several syn- and post-impact processes – including crater excavation and modification (rebound), melt pressure increase, isostatic uplift, cooling, and tectonism – have been proposed to be mechanisms responsible for the dilation of fractures and subsequent emplacement of one or more melts. The timing and duration of these processes vary considerably, and each has very different implications for a) the timing and mechanism of offset dike emplacement within the evolution of the SIC, b) the timing of inclusion generation and sulfur saturation in the SIC, and c) exploration vectors for targeting mineralization in offset dikes. For example, most models advocating flowage differentiation have implicitly assumed laminar flow, but several of the most favoured emplacement mechanisms involve very rapid (hypersonic) injection and therefore turbulent flow. Regardless of the rate of emplacement, multi-stage injection is supported by the common presence of inclusions of QD within MIQD, sharp contacts between QD and MIQD, and the spatial relationship between marginal QD and interior MIQD. The objective of this research project is to more rigorously test models for the emplacement of the offset dikes in the SIC through detailed geological, petrographic, geochemical, and fluid dynamic studies.

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IS THE LABRADOR TROUGH PROSPECTIVE FOR MAGMATIC NI-CU-PGE SULPHIDE DEPOSITS?

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The Palaeoproterozoic Labrador Trough in northern Québec is the focus of ongoing exploration for magmatic Ni-Cu-PGE sulphide deposits. Mafic-ultramafic rocks of the Montagnais Sill Complex (~ 1.88 Ga) comprise several styles of magmatic sulphide mineralisation hosted in aphyric, (glomero)porphyritic, and cumulate-bearing gabbroic sills, that intrude sulphidic metasedimentary rocks. To date, only sub-economic occurrences have been discovered, which begs the question as to whether the Labrador Trough is prospective for economic magmatic ore deposits.

The recently discovered Idefix PGE-Cu and Huckleberry Cu-Ni-(PGE) prospects provide important insight into the mineral potential of the Labrador Trough. The Idefix prospect consists of a > 200-m-thick stack of aphyric gabbroic sills that are host to PGE-dominated disseminated sulphides (0.4 g/t PGE, 0.4% Cu). The Huckleberry prospect is a ~ 400-m-thick, sill complex, comprising an older stack of (glomero)porphyritic gabbro sills intruded in its centre by a differentiated gabbro-wehrlite sill. In addition, anastomosing websterite sills protrude from the gabbro-wehrlite sill into the glomeroporphyritic gabbro footwall. Of particular interest, is net-textured sulphide mineralisation (1% Cu, 0.2% Ni, and 0.7 g/t PGE) in the ultramafic units that has percolated downward into the underlying glomeroporphyritic gabbro footwall.

The country rock consists of Archaean and Palaeoproterozoic sediments with high S/Se (≤ 30,000) and $\delta^{34}S$ (17.2 ± 1.2) values, and variable $\Delta^{33}S$ (0.01-0.17) values. Most magmatic sulphides have low S/Se values (< 4,000), with magmatic $\delta^{34}S$ and $\Delta^{33}S$ signatures. These observations combined with whole-rock geochemistry suggest that the parent magmas assimilated little if any, crustal material. Chalcophile element geochemistry from both prospects suggests immiscible sulphide was entrained from elsewhere in the plumbing system, indicating greater mineralisation is yet to be found in the Labrador Trough.

BLACK SHALE PARTIAL MELTING EXPERIMENTS PROVIDE INSIGHT INTO S, C, AND CU ASSIMILATION PROCESSES IN DULUTH COMPLEX, MINNESOTA

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Black shale assimilation is the most plausible trigger mechanism for the formation of the magmatic Ni-Cu-PGE deposits in the 1.1 Ga Duluth Complex, Minnesota. The Duluth Complex magmas assimilated large proportion of S from the footwall black shales of the Paleoproterozoic Virginia Formation, which enhanced sulfide saturation in the magmas. Consequently, the sulphide deposits occur systematically close to the footwall rocks and are often associated with abundant Virginia Formation xenoliths. The details of the mode of S transport during the assimilation are not fully understood. Both fluid and melt phases are likely to mobilize S during contact metamorphism and partial melting of the black shale, but the relative contributions of these different media have not been constrained yet.

We collected a pristine Virginia Formation black shale sample outside the thermally affected contact aureole of the Duluth Complex and conducted partial melting experiments at 2 kbar, 700–1000 °C. These P-T conditions are in agreement with conditions estimated for the footwall rocks and Virginia Formation xenoliths in the Duluth Complex. The experiments revealed that incipient subsolidus dehydration of hydrous silicates at 700 °C leads to mobilization of majority of S, C, and Cu into the fluid phase. Mass balance calculations indicate that in addition to S, large portion of Cu in the Duluth Complex deposits could also derive from the Virginia Formation via fluid transportation. Subsequently, Cu-rich sulphide melt and Cu-Ni-bearing pyrrhotite droplets form at 1000 °C, when silicate melt becomes the dominant phase. Cu and Ni from the fluid and silicate melt partition into these droplets providing a mechanism of initial concentration and extraction of the chalcophiles during (partial) assimilation of the wall-rock. The sulphides are typically attached to fluid bubbles at 1000 °C, which enhances assimilation from the footwall by buoyant transport.

SULFIDE AND SULFATE SATURATION OF DACITIC SILICATE MELTS AS A FUNCTION OF OXYGEN FUGACITY

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Sulfur (S) is a key element in terrestrial magmatic processes and yet one of the most difficult to model due to its heterovalent chemistry and volatile nature. The maximum amount of S a silicate melt can dissolve before saturating with sulfide or sulfate changes with the prevailing redox state of the system and has important implications for the S budget of a system. Although a number of models have been developed to predict the S content of a silicate melt at either sulfide (under reducing conditions) or sulfate (under oxidizing conditions) saturation, only one model to date systematically assessed the sulfide-sulfate transition region at intermediate oxidation states (~ΔFMQ+1 to ~ΔFMQ+2). That model was developed using experimental data that constrain the S content at sulfide saturation and S content at sulfate saturation of basaltic silicate melts and its applicability to chemically evolved melts rests on the assumption that melt composition does not affect sulfide and/or sulfate solubility as the S in the melt changes from S^{2-} to S^{6+}.

Here we report new experimental data to assess the effect of melt composition on sulfide and sulfate saturation in a dacitic silicate melt across the sulfide-sulfate transition. We present six experiments conducted using an H_2O-saturated natural dacitic silicate melt at 1000°C, 300 MPa, and oxygen fugacity encompassing the entire sulfide-sulfate transition (log fO_2 = ΔFMQ-0.7, ΔFMQ+0, ΔFMQ+0.5, ΔFMQ+1, ΔFMQ+1.75 and ΔFMQ+3.3). When our results are compared with previous studies, we are able to show that the existing model developed using a basaltic silicate melt does not fit the observations of sulfide and sulfate saturation at intermediate oxidation states (~ΔFMQ+1 to ~ΔFMQ+2) in a dacitic silicate melt. This discrepancy provides evidence that melt composition does affect how sulfide and sulfate dissolve in silicate melts and we propose a new model for the behavior of sulfide and sulfate saturation in evolved magmatic systems.