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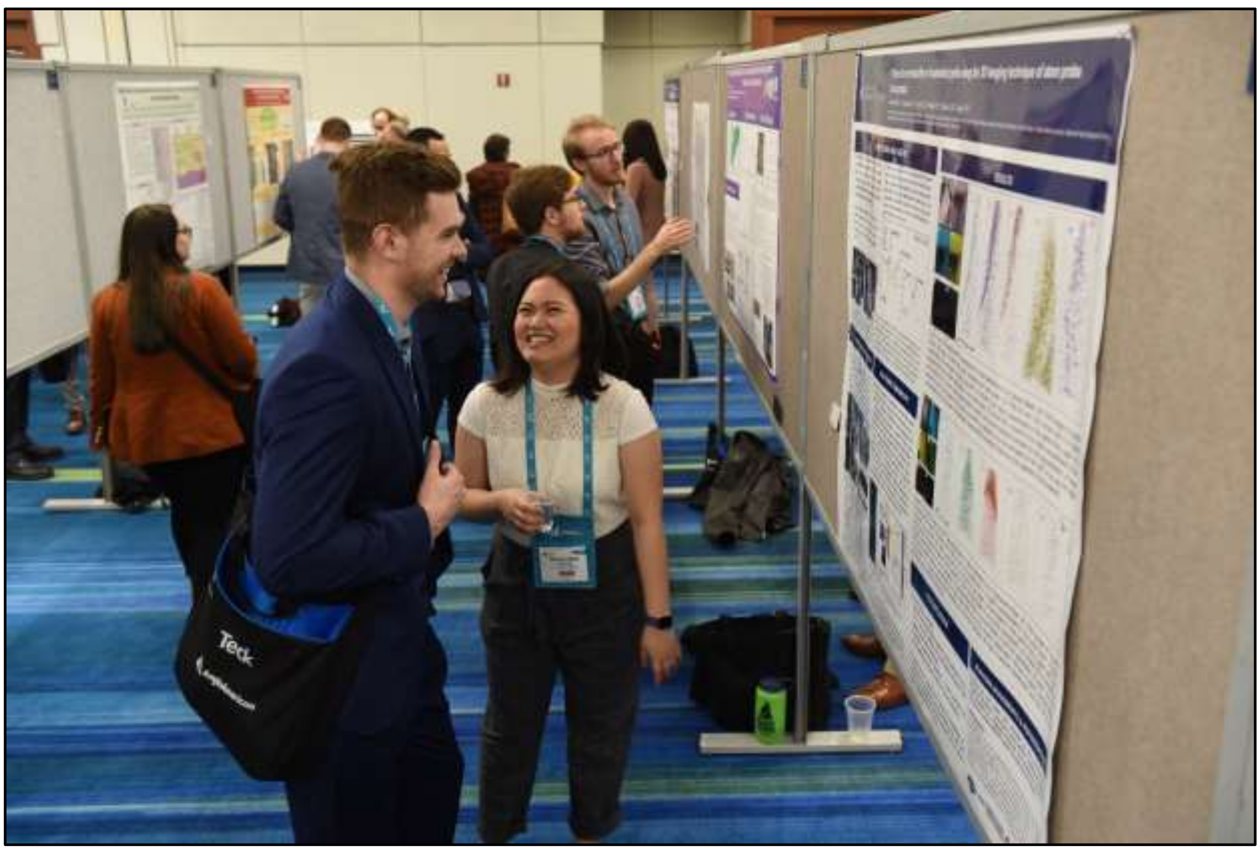

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Sedimentary Environments

The Effects of Cordilleran Deformation on the Howard's Pass XY deposits, Yukon

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The Shale-hosted Massive Sulphide Deposits of Howard's Pass are some of the world's most well-endowed Zn-Pb resources. Sulphide deposition occurred in the Silurian and the deposit was deformed during the Cretaceous Cordilleran orogeny. A recent model proposes that the deposits are hosted within a regional shear zone where bedding has been completely transposed and previously interpreted stratigraphic boundaries are tectonic in origin. This current study aims to test this model and is focused on the XY group of deposits at the eastern end of the Howard's Pass district. Lithostratigraphic mapping and structural observations indicate one main phase of folding, F_1, and the XY group of deposits is located on the southern limb of a macroscopic syncline. F_1 folds are upright and gently plunging to the WNW-NNW. A regionally developed, steep NE dipping, cleavage, S_1, is axial planar to the F_1 folds across Howard's Pass. S_1 typically manifests as a slaty cleavage comprising pervasively developed dissolution seams. Within the mineralized sections at XY, S_1 forms spaced sulphide-rich dissolution seams that were previously interpreted as dewatering structures. A later kink fabric, S_k, is seen locally and may be genetically linked to a movement on WNW and NNE striking faults that overprint the F_1 folds. Mapping shows that the geometry of the deposits is primarily controlled by folding and that contacts between units are stratigraphic in origin. S_1 and S_k are the only foliations mapped. No shear zone fabrics were identified and there is no evidence that bedding has been transposed.

Structural evaluation of the Tom Deposit, Selwyn Basin, Yukon

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Stratiform Pb-Zn orebodies that make up shale-hosted massive sulphide (SHMS) deposits account for 40% of Zn and 60% of Pb reserves globally. SHMS deposits form at shallow depths and low temperatures in reduced sedimentary basins from upwelling hydrothermal fluids that circulate through the sedimentary sequence scavenging metals during extension. Fluid circulation is dependent on faults to provide vertical permeability across sedimentary layering. The structural geology of basin genesis along synsedimentary fault conduits is crucial to understanding the formation of Zn-Pb-Ag shale-hosted stratiform sulphide deposits. Fluid circulation is dependent on faults to provide vertical permeability across otherwise impermeable sedimentary layering. Defining a basin's fault architecture is a critical step in reconstructing basin geometry and identifying prospective areas for SHSS mineralization. The Selwyn Basin, Yukon, formed during the Neoproterozoic to Lower Devonian extensional rifting, where a large marine depocentre formed along the northern Laurentian passive margin. The Selwyn Basin comprises a sequence of clastic sedimentary rocks that host several large SHMS deposits, including the Tom and Jason deposits of the Macmillan Pass area. These deposits are hosted in Devonian strata that have been extensively folded by mid-Cretaceous crustal shortening. This study's principal objective is to decipher the structural evolution of the Macmillan Pass area and evaluate the fault geometry and structure of the Tom deposit to identify faults that may have controlled hydrothermal fluid flow and SHMS mineralization. This project intends to improve upon previous local mapping in the Macmillan Pass area and advance the structural understanding of the Cordilleran deformation's effect on SHMS mineralization in the Selwyn Basin. Evaluating the Macmillan Pass area's structural controls and identifying fault geometry and kinematic histories further define the structural geometry, spatial variation in strain accommodation, overprinting relationships, and current state of SHMS mineralization seen at the Tom Deposit.

The provenance, depositional environment and metallogenic implications of the Ament Bay metasedimentary assemblage, Sturgeon Lake Greenstone Belt, northwest Ontario

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The Ament Bay metasedimentary assemblage (ABMA) is the youngest clastic assemblage in the Savant Lake-Sturgeon Lake greenstone belt (SSGB), and is interpreted to have an alluvial-fluvial origin. However, its age, provenance and its contact relationships with surrounding greenstone assemblages are poorly understood. The SSGB makes up the eastern part of the Western Wabigoon terrane of the Superior Province. The greenstone belt dominantly consists of Neoarchean submarine bimodal volcanic rocks and clastic rocks, both of which have been intruded by widespread felsic plutons and gabbroic dykes/sills. The supracrustal assemblages are steeply dipping and form a regional-scale syncline, with the ABMA exposed along the hinge. The ABMA is surrounded by felsic and mafic volcanic rocks that compose the Central and South Sturgeon Assemblages. The ABMA dominantly consists of conglomerates, sandstones and greywacke-mudstone successions, which all have been affected by a penetrative deformation resulting in foliation sub-parallel to oblique to bedding. The ABMA is found spatially associated with alkalic magmatism and likely consists of locally derived debris. This draws comparisons to gold-prospective Timiskaming-type basins elsewhere in the Superior; however, the ABMA is poorly endowed relative to some of the gold-rich Timiskaming sediments in the Abitibi greenstone belt. This study will address factors controlling metal endowment in Neoarchean late-orogenic basins. This is a Metal Earth publication number MERC-ME-2021-026.

Using sulfide trace element geochemistry for constraining mineralization paragenesis by LA-ICP-MS: an example from a sediment-hosted Cu-Co deposits in northwestern Namibia

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Substitution of major elements by trace elements may occur in minerals primarily according to Goldschmidt's Rules. Trace elements tend to display preferred partitioning between co-crystallized sulfide phases. Sulfide trace element signatures and trends have been widely used to constrain ore type and identify separate ore-forming generations. Recent studies have been investigating the effects of metamorphism on the trace element composition of sulfides. Conventional paragenetic descriptions, principally based on microscopy, cannot identify multi-generational geochemical variations and chemical zoning, which LA-ICP-MS analyses can. Our study demonstrates that variance in and grouping of sulfide trace element concentrations can be applied to discriminate a multi-phase origin of a sediment-hosted Cu-Co deposit. In situ analyses of sphalerite, chalcopyrite, pyrite and pyrrhotite form six different mineralization styles revealed that both distinct geochemical similarities and differences exist between the analyzed sulfides from the different mineralization types. The data suggests that part of the main Cu-Zn mineralization may be the result of trace element liberation and remobilization during the Pan-African Damara Orogeny. Our results suggest that the Damara Orogen may have had a larger impact on the formation of the sediment-hosted Cu-Co Dolostone Ore Formation deposit than previously believed, as it was generally assumed that the mineralization was dominantly of diagenetic origin. This is similar to what has been observed in the Zambian part of the Central African Copperbelt (CACB), where the Pan-African Lufilian Orogen has overprinted any possible pre-existing mineralization. The characteristics of the metal-bearing fluids are still unresolved for the Dolostone Ore Formation, but trace element compositions of the sulfides reveal a multi-stage mineralization and demonstrates that LA-ICP-MS is a strong tool, to resolve mineral assemblage paragenesis, alongside convention microscopy. One aspect that is yet tested, and may affect the observed trends, is deposit-scaled trace element zonations, additional data from more samples are required to evaluate the impact of such a zonation.

Volcanogenic Massive Sulfide (VMS) Deposits

Tectonism, magmatism, and hydrothermal venting in the Mariana back-arc

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Hydrothermal systems, in general terms, are controlled by a complex interaction between permeability and heat source, on the seafloor when the specific conditions are met, these interaction gives rise to the formation of large and deep geothermal systems whose surface expressions are known as black smokers and are characterized by the mineralization of massive sulfides, juveniles analogs of the VMS deposits mined on land for their content of ore minerals. However, studying these deposits in the ocean is challenging due to the impossibility of using traditional geological, geophysical, and geochemical mapping methods. In the first part of our research, we used remote predictive mapping to create geological maps in the Mariana Back-arc as an initial and fundamental step in understanding the distribution of faulting and magmatism in the area. From identification of morphological features in high-resolution bathymetry, the interpretation of formations is performed combining direct observations of the ocean floor, samples, acoustic backscatter, seismic reflection profiles, and regional compilations of satellite, airborne, and marine magnetic and gravity data, the interpretations are then extrapolated to areas with less information and with similar morphologies to create geological maps at a 1: 1 million scale. Preliminary results of the structural mapping allow us to carry out the analysis of how the distribution and density of the faults vary along the back-arc and the possible role of factors that occur in subduction zones such as trench geometry, subduction-zone collisions, variations in spreading rates, and proximity to the arc. This project's results will be used in further research as inputs to develop prospective methods for seafloor massive sulfide deposits in the area.

Melt inclusions associated with Archean volcanogenic massive sulphide deposits: constraints on the pre-eruptive metal and volatile content of magmas

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The Kidd Creek and LaRonde Penna Archean VMS deposits, Abitibi greenstone belt, differ greatly in metal tenor and tonnage, in particular in Au endowment. In this study, primary melt inclusions in zircon hosted in pre-, syn-, and post-VMS ore volcanic units will provide compositional constraints on the initial metal and volatile chemistry of the magma before eruption, allowing a comparison of the precursor metal budgets of magmas that actively degassed, and/or were passively leached, to supply metals to the deposits. Primary methodologies in progress include: (i) thin section petrography to identify lithologies containing zircon and to assess the overall abundance of zircon, and extent of alteration of the volcanic rocks, which impacts the preservation of melt inclusions; (ii) melt inclusion petrography (origin, preservation, degree of recrystallization, size, depth, shape, presence of accidentally trapped phases, etc.); (iii) scanning electron microscopy (SEM-EDS and -BSE) for semi-quantitative determinations of bulk inclusion composition of exposed melt inclusions; (iv) electron microprobe (EPMA) to identify daughter and accidentally trapped phases, and (v) laser ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS) to quantify major/trace element composition of melt inclusions (including metals) and host zircon chemistry. Magmatic zircons in footwall and hanging wall rhyolite units of the Kidd Creek VMS deposit contain silicate and phosphate mineral inclusions (50% of total inclusions), silicate melt inclusions (40%) and sulphide (melt and/or mineral) inclusions (~10%). Mineral and melt inclusions in zircon occur in primary growth zones. Mineral inclusions (1.5-60 µm) occur as needle-like to euhedral-subhedral lath-shaped crystals and are dominantly apatite with lesser occurrences of biotite and amphibole. Silicate melt inclusions (1.5-35 µm) of rhyolitic composition range in shape from spherical and irregular blebs to sub-angular, elongated inclusions, are microcrystalline (recrystallized), and monomineralic to polymineralic. They are comprised dominantly of quartz, apatite, alkali-feldspars, biotite, pyroxene, and amphibole in varying proportions. Other minerals identified include xenotime and ilmenite. Sulphide inclusions (1.5-15 µm) occur as rounded to sub-rounded spherical blebs, and are composed of pyrite, chalcopyrite and/or pentlandite. This first study of melt inclusions in Archean VMS systems aims to provide insight into their magmatic evolution. Petrographic and compositional data from the melt inclusions will be combined with zircon compositional data to elucidate links between the magmatic P-T-fO_2 evolution and metal and volatile endowment, providing a means to quantitatively inform mass balance exercises concerning the magmatic contributions to VMS, and differentiate between metal-barren and -fertile volcanic districts. The is Metal Earth publication number MERC-ME-2021-022.

Redefining the stratigraphy associated with the Canagau and Ehrhart properties of the Ben Nevis Volcanic Complex (Ontario, Canada)

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The Canagau and Ehrhart properties located within the Ben Nevis Volcanic Complex are part of the Blake River Group (2704 to 2695 Ma) of the Abitibi greenstone belt. These properties exhibit polymetallic VMS-style mineralization (Cu-Pb-Zn-Ag-Au) and are predominantly hosted in a monolithic felsic tuff breccia. Mineralized veins containing disseminated pyrite (± sphalerite ± galena ± chalcopyrite) crosscut the stratigraphy of the area. Detailed lithostratigraphic mapping of the Ben Nevis Volcanic Complex refined the stratigraphy into seven distinct units, which range from massive to pillowed mafic volcanic rocks intercalated with coherent rhyolite to tuff breccia and ash tuff. Correlation of lithostratigraphic units is based on distinctive lithofacies such as the presence of pumice fragments and finely bedded felsic volcanic ash. Pillowed mafic flows and normally graded beds define a consistent stratigraphic facing direction and lateral facies variations indicate a progression into a more mafic environment. This redefined stratigraphy indicates a succession from a subaqueous environment of mafic pillowed flows, felsic volcaniclastic mass-flow deposits and synvolcanic dykes with peperite margins, which transitions to explosive pyroclastic volcanism and low-angle, cross-bedded felsic tuffs, potentially indicative of pyroclastic surge deposits in a subaerial environment. Typical VMS style alteration (i.e., chlorite, epidote, carbonate and sericite) is observed in the field and confirmed using petrography and whole-rock lithogeochemical analysis. Mass balance calculations to quantify the mass flux within each unit will be compared to the newly defined lithostratigraphic units associated with the Canagau and Ehrhart properties. This study refines the depositional environment, volcanic architecture, alteration, and mineralization surrounding the Canagau and Ehrhart properties to further understand processes that may have led to local and regional metal endowment within the Blake River Group. This is a Metal Earth Publication No MERC-ME-2021-006.

U-Th Dating of Submarine Hydrothermal Sulfides along Mid-Ocean Ridges

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The study of seafloor hydrothermal systems and associated seafloor massive sulfide (SMS) deposits has generated significant interest over the past 40 years. Time is a critical component for understanding the formation and evolution of SMS deposits, including the time required to form deposits large enough to be economically interesting. The $^{230}Th/^{234}U$ technique is the most commonly applied chronometer for dating accumulations of submarine sulfide minerals. This study applies this technique to samples collected from several seafloor vent fields for which no age data is yet available, and to test if this technique yields similar results to other techniques that have already been applied to vent fields (e.g., $^{226}Ra/Ba$). Three locations have been chosen for dating using the $^{230}Th/^{234}U$ dating method; Endeavour, on the Juan de Fuca Ridge; 9°50'N, on the East Pacific Rise; and Loki's Castle, on the Arctic Mid-ocean Ridge system. Ages yielded from the $^{230}Th/^{234}U$ dating method: i) provide insights into the longevity of hydrothermal systems, ii) test the hypothesis that hydrothermal systems turn on and off over time, iii) provide data to assess the metal fluxes to the ocean, and associated sulfide mass accumulation rates, iv) link hydrothermal venting to tectonic and volcanic process at MORs, and v) help evaluate the sustainability of seafloor mining.

Structural Framework and Remobilization of Gold at the Goliath deposit, Western Wabigoon Subprovince, Ontario

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The Goliath gold deposit is in the Western Wabigoon Subprovince, near Dryden Ontario. The deposit has a measured and indicated resource of 16.2 Mt at an average grade of 2.29 g/t Au and 8.2 g/t Ag. The deposit also contains an inferred resource of 2.0 Mt at 3.43 g/t Au and 8.8 g/t Ag. The deposit is located north of the Wabigoon deformation zone and is hosted in a highly deformed volcano-sedimentary complex (2775-2700 Ma). The Goliath deposit is interpreted to be a synvolcanic / synsedimentary deposit that has undergone intense alteration followed by deformation and metamorphism. Three deformation events have affected the deposit. D_1 is a compressional event with a north-south shortening, forming tight to isoclinal F_1 folds and a strong axial planar S_1 foliation. D_2 is a transpressional event that caused dextral shearing, local Z-shaped (F_2) folds, and a weaker S_2 foliation. D_3 is a brittle event and is associated with a minor northwest fault. Gold mineralization at Goliath is associated with base metal sulfides, predominately pyrite, sphalerite, and galena, as well as a strong potassic alteration, typically seen as sericite. Sulfide mineralization is hosted in steeply dipping and highly deformed felsic volcanic rocks within the S1 foliation plane as narrow planar veinlets. The highest gold grades form ore shoots which are consistent with the intersection between the S_1 and S_2 foliation planes suggesting the mineralization was remobilized from the deformation events into this predominate orientation. Gold is located in fractures and along the grain boundary of the pyrite grains and is interpreted as remobilized gold from within pyrite grains. The gold mineralization at Goliath is interpreted to be controlled by two events; (1) an early syngeneic stage comprising base metal sulphide mineralization and intense sericite alteration, and (2) a secondary remobilization stage that resulted in the localisation and concentration of gold into the S_1/S_2 intersection lineation. This is Metal Earth Publication No. MERC-ME-2021-030.

Volcanism and hydrothermal venting on a hot-spot influenced slow-spreading mid-ocean ridge

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The Reykjanes Ridge is a spreading ridge that presents an opportunity to track the evolution of rifting centers at an asymmetric slow-spreading plate boundary. The ridge spans the northern ~1000 km of the Mid Atlantic Ridge and has been spreading at a full spreading rate of ~20 mm/year. A unique feature of the ridge is that it spreads obliquely to the spreading axis: a consequence of the change in spreading direction from ~125 to ~100 degrees due to the failure of the triple junction between the Greenland, Eurasian, and North American plates 37 Mya. Along with the sudden change in orientation, disjunct ridge segments were formed and separated by transform faults which have been continuously eliminating through strike-slip motion from north to south, thereby re-establishing the original linear geometry of the ridge. The southern extent of the ridge is the latest to reorganize but remains in a state of active tectonic deformation as demonstrated by the gradual lengthening of spreading segments and migration of non-transform discontinuities (NTOs). This increase in the length of spreading centers suggests an increase in magma supply and crustal permeability, but the precise cause is unknown. Investigating the geodynamic control on the style and extent of rift-valley volcanism is possible with the application of a novel remote-predictive geological mapping method based on interpretations from newly acquired bathymetric and acoustic backscatter data. Notably, the bathymetric data provides significant high-resolution coverage of both on-axis and off-axis regions, allowing the monitoring of the evolution of the ridge for up to 10 Mya. The acoustic backscatter data aids in the interpretation of geologic features and terrains whose distribution and morphology reflect both present-day and historic ridge dynamics. This analysis will produce new insight of the on-going first and second order deformation of the Reykjanes Ridge, its controls, and its effects on rift-valley volcanism and potential locations of hydrothermal venting.

Piecing together the complex geologic history of the Nash Creek Deposit: Using geologic modelling to create a deposit model

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The Nash Creek Deposit (NCD) is a Volcanogenic Massive Sulphide (VMS) deposit located in New Brunswick, approximately 65 km NW of the Bathurst Deposit, in the Northernmost segment of the Appalachians. The NCD is a zinc, lead and silver deposit, hosted within the Jacquet River Syncline that is yet to be modelled using modern 3-D software. The deposit is contained within Early Devonian rocks and the Nash Creek graben, that is made up of the Black Point-Arleau fault and its offsets. This graben was active at the time of deposition and is believed to have had major effects on the formation of the NCD. Previous studies have shown that there is potential for the NCD, but not until there is a better understanding of the geologic constraints of the deposit. This study aims to create a three-dimensional model of the NCD that can be used to elucidate some of the unknowns of the structural geology; including determining the origin of the late mafic intrusions, the potential structural constraints of the mineral deposits, and determining patterns of mineralization. This deposit model will be compared to the major traits of VMS archetypes to determine potential traits that could be used to further constrain the deposit. This study's expected outcomes are to determine the depths and lithologies that contain the highest grades of mineralization, create an updated regional geology map, and to create a 3D model that shows the structural geology of the deposit. Results from this study could be used to understand the emplacement of the late mafic intrusions in the NCD and enhance the knowledge of the surrounding structural geology.

Quantifying the metal budgets of seafloor hydrothermal systems: examples from the East Manus basin and from the Lucky Strike hydrothermal field

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Volcanogenic massive sulfide (VMS) deposits are polymetallic mineral deposits presently being mined around the world. They provide a valuable source of precious and base metals to the world economy, so it is important to have a fundamental understanding of their depositional environment and the conditions necessary to form large, economically-viable deposits. Seafloor massive sulfide (SMS) deposits are the modern equivalents to VMS deposits, forming at or just below the seafloor where hydrothermal venting occurs, meaning their study provides the unique opportunity to directly study an ore forming process. The metals precipitating within SMS deposits are either leached from the crust below the deposit or introduced by direct magmatic volatile input. We compare the total available leachable metals, estimated by volume calculations of hydrothermal reaction and upflow zones from two different sites that are hosted in different tectonic settings. The Tumai Ridge in the East Manus Basin (back-arc setting), which is known for having input of metals directly from magmatic degassing, and the Lucky Strike hydrothermal field (mid-ocean ridge), where leaching of the crust is the dominant source of metals. With the volume measurements, metal budget estimates can be calculated for these two hydrothermal systems, establishing a methodology for quantifying a hydrothermal system's economic potential as well as studying the conditions needed to form a world-class sized VMS deposit. Furthermore, analysis of the hydrothermal upflow models allow for approximations to be made on the volume of leachable crust exposed to the degassing magmatic volatiles, providing a quantitative method for evaluating the significance of magmatic volatile metal input into the hydrothermal system's overall metal budget. In addition, we estimate the upper limits of Cu, Zn, and Au content at these two sites if all the metal available via leaching was transported and deposited as SMS deposits.

Using pyrrhotite trace element chemistry for better insight of the mineralization in the Sullivan Deposit, B.C.

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The Sullivan Deposit, B.C. hosted in the Belt-Purcell Supergroup, is one of the most significant areas for sedimentary exhalative style base metal mineralization. The Sullivan deposit produced 161.97 Mt of Zn (5.86%), Pb (6.08%), Ag (67.36 g/t) as a massive past-producer within the Belt-Purcell Supergroup. The Sullivan Deposit is the essential mineral deposit in the Canadian portion of the Belt-Purcell Basin. The formation of the Sullivan Deposit occurs beneath the contact within the Lower and Middle Aldridge Formation. The top of the Middle Aldridge Formation consists of black laminated mudstone defined as carbonaceous wacke laminite by Cominco. The extensive hydrothermal alteration occurred in the Sullivan Deposit by a variety of alteration processes. The most effective one is Sericite alteration, which can be observed as a distinctive pale yellowish grey-green colour since the sulphidation of biotite, which forms pyrrhotite and muscovite during metamorphism. Mining exploration has a variety of challenges since the exploration methods are significantly expensive and time-consuming. Because of these reasons, new strategies must be developed on known deposits. In the current project, we will endeavour to improve new instruments to search for new sedimentary exhalative style deposits in the Belt-Purcell Basin, focusing on in situ analyses of specific phases. Notwithstanding, the base to building any good micro- or nanoanalytical study is always detailed petrology. The focus of this presentation is that petrology. Here we present reflected light images and EPMA data of the samples from the Sullivan deposit's host horizon, increasing the range from the deposit. Notably, we highlight the various generations of the sulphide species that occur within the host horizon and how these change with proximity to the mineralizing source.

Black smoker fluid fluxes at the Niua South seafloor hydrothermal vent field, Tofua-Kermadec Arc

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Niua South is a crater-hosted seafloor hydrothermal vent field located on a submarine arc volcano along the Tofua-Kermadec arc, near Tonga in the South Pacific Ocean. In 2016, scientists onboard the R/V Falkor visited Niua South and, over two weeks, surveyed the crater with a high-definition video camera mounted on a remotely operated vehicle (ROV), and collected rock samples from the hydrothermal vents. Here, we present results from a study of the chemical mass balance of Niua South and the depositional efficiency of the system. The flow rates of metals entering the system are calculated through video analysis of fluid discharge rates from black smokers. The velocity and volumetric flux of discharging fluid is determined from the dive videos using PIVLab, a specialized MATLAB program for extracting velocity information through image analysis. These data are combined with vent fluid composition, the age of the deposit, and deposit composition, and size, to calculate the proportion of metals mobilized by the hydrothermal system that are deposited on the seafloor. The results from this study provide insights into the depositional efficiency and total metal flux generated by the Niua South hydrothermal system. Furthermore, these results show the ratio of high to low temperature venting and the input, output, and distribution of metals within the system. This research will address longstanding questions about the chemical mass balance of hydrothermal systems and the fate of metals at the seafloor, which has implications for understanding rates of formation of volcanogenic massive sulfide (VMS) deposits.

Geochemical characterization and comparison of the seafloor massive sulphide deposits of the Niua Volcanic Complex and the Jean-Charcot Troughs, SW Pacific

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Hydrothermal seafloor massive sulphide (SMS) vent sites are a relatively common, but practically inaccessible phenomenon associated with tectonic plate boundaries on the ocean floor, and tend to form as characteristic black-smoker chimneys and associated sulphide mounds. These vent sites are the result of the circulation of seawater in convection cells within the oceanic crust, and are driven by anomalously high geothermal gradients, which can result in the mobilization and redeposition of concentrated metal cations, forming potential ore deposits. This study focuses on two distinct SMS sites in the SW Pacific, near Fiji. The Niua Volcanic Complex vent site is associated with volcanic arc deposits, and was produced by the westward subduction of the Pacific plate beneath the Indo-Australian plate. In contrast, the Jean-Charcot Troughs' back-arc basin SMS deposits were produced by the eastward subduction and subsequent rollback of the Indo-Australian plate beneath the Pacific plate. The geochemistry of SMS deposits is not consistent between vent sites, and instead appears to be influenced by a variety of physical and chemical parameters, including temperature, pH, REDOX conditions, salinity, host rock assemblage, boiling, and tectonic regime. These factors influence the spatiotemporal controls of deposition and the allocation of trace elements within sulphide host minerals such as pyrite, sphalerite, galena, chalcopyrite, and others. However, it is not currently well understood which physical and chemical parameters necessarily dictate the distribution of trace elements within these minerals, and how these distributions evolve over the hydrothermal history of these vent systems. By comparing trace element distributions across a variety of low-temperature sulphide minerals from hydrothermal vent sites associated with both the Niua Volcanic Complex and the Jean-Charcot Troughs, and thereafter comparing those results to previous geochemical analyses from different tectonic settings, a framework of geochemical constraints and controls on ion mobility and trace element affinity can be established. Our results demonstrate how physiochemical parameters influence trace element distributions, and can be used to produce predictive geochemical models for other SMS deposits across the seafloor. This work can be used to provide future researchers and potential prospective expeditions with predictive models of how trace elements are distributed within the host minerals of these hydrothermal vent sites. Likewise, this work can also be used to reconstruct the hydrothermal history of a vent site, ideally based solely on the trace element distribution of the host sulphide minerals and the spatiotemporal relationships between those host minerals.

The Sb-Au-district Brandholz/Goldkronach (Fichtelgebirge, Germany): mineralogical indications for the evolution of hydrothermal Sb-mineralization

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The Brandholz/Goldkronach district is situated in the southeastern part of Germany in the Bavarian Fichtelgebirge. Previous literature on the mineralogy of the district is rather descriptive and modern geochemical analysis is entirely missing. In this contribution, we combine petrography, bulk rock-geochemical analysis, SEM-MLA as well as EPMA to infer precipitation mechanism and ore-forming processes. The quartz-polymetallic-sulfide veins are hosted in Ordovician shists, called "Phycodenschiefer", which were intruded by upper Devonian meta-basalts. Antimony-sulfides are the main ore mineralization inside of the quartz-veins, accompanied by minor auriferous arsenopyrite and pyrite. Petrographic observations suggest precipitation of an early stibnite phase (stage I). Sb-Pb-sulfides/sulfosalts (stage II) precipitated in fractures and fissures of stage I stibnite with a slight change to Pb-rich Sb-phases. The antimony-mineralization event evolved from stibnite (Sb_2S_3), over fülöppite ($Pb_3Sb_8S_{15}$), zinkenite ($Pb_9Sb_{22}S_{42}$), plagionite ($Pb_5Sb_8S_{17}$) to boulangerite ($Pb_5Sb_4S_{11}$). Chemical analyses corroborate the petrographic observations and indicate a change in the hydrothermal environment from an Sb- to Sb-Pb dominated system with a distinct geochemical change from Pb-free to Pb-containing Sb-phases. Characterization of the precipitation sequence can be used to improve the understanding of the hydrothermal evolution of the whole Sb-Au-ore system in Goldkronach.

Pb isotopic constrains on the genesis of the Toyoha deposit, Hokkaido, Japan: Implication for exploration of Indium-bearing epithermal polymetallic deposit

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Indium is a critical metal for today's society, which is widely used in liquid crystal displays for computers and smartphones. The Toyoha epithermal polymetallic deposit in Hokkaido, Japan, used to be the largest indium producer in the world in the 1990s, containing 4,700 t indium in total. Previous studies have revealed that the Toyoha mineralization is divided into two stages based on cross-cutting relationships; the earlier (2.9-1.6 Ma) and the later (2.7-0.5 Ma). Since the later veins are characterized by a particularly high grade (300 ~ 400 ppm indium on average), a comparison of the genetic aspects of these veins provides an excellent opportunity to elucidate the mechanisms of indium enrichment. Here we investigated the Pb isotopic composition of sulfide (sphalerite, chalcopyrite, and pyrite) from both the indium-poor earlier veins and the indium-rich later veins together with the volcanic and sedimentary rocks in the Toyoha area. Our results show that the Pb isotopic compositions of the earlier veins fall within the range of the Muine volcanic rocks (3.2–2.9 Ma) at the south of the Toyoha area and the Miocene volcanic and sedimentary rocks which host the earlier and later veins. This indicates that a magma isotopically similar to the ones extruded to the Toyoha area contributed to the mineralization of the earlier veins. In contrast, some samples from the later veins yield more radiogenic 206Pb/204Pb compositions than most of the known volcanic rocks in the Toyoha area, overlapping with the isotopic composition of the Quaternary basalt and basaltic andesite of Southwest Hokkaido. Since no Quaternary igneous rock is known to be exposed in the Toyoha area, the magma which was involved in the mineralization of the later veins likely stayed at depth before and after the mineralization, or a deep geofluid derived from the subducted Pacific plate may have been involved in the mineralization. This leads us to propose that a focused flow along faults can effectively transport metal-rich fluid released at depth, resulting in high-grade polymetallic mineralization. The reported high geothermal potential of the Toyoha area also suggests the presence of a focused fluid flow from depth, supporting our hypothesis. Therefore, areas with high geothermal potential without Quaternary volcanism, like Toyoha area, might be suitable exploration targets for similar indium-rich polymetallic deposits in southwest Hokkaido.

Intrusion-related Deposits

Mineralization styles in the distal Zn-Pb(-Ag) skarn deposit of Santander, Central Peru

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In proximal skarns, overprinting between skarn and porphyry-type mineralization is a relatively common process. In distal skarn settings, where the causative intrusion is frequently unknown, such an overprint is rarely observed and the extension of alteration and mineralization is difficult to estimate. Definition of the spatial distribution of different mineralization styles in distal skarn deposits allows for better targeting of exploration and estimation of the overall extension of the mineralized system. The Miocene Polymetallic Belt of Central Peru hosts numerous porphyry, skarn and polymetallic (Cordilleran) deposits genetically associated with the emplacement of fertile porphyry stocks of Oligocene and Miocene age. The Santander deposit, located in the central part of the belt, is defined as a distal Zn-Pb(-Ag) skarn and carbonate-replacement deposit, based on its mineralogical, textural, alteration and host-rock features. The deposit is hosted by the carbonate sequences of the Lower to Upper Cretaceous Pariahuanca, Chulec, Pariatambo and Jumasha formations and consists of several discrete mineralized centers structurally controlled by a series of NW-trending regional faults, anticline and syncline fold structures. Based on a systematic petrographic, textural, mineralogical and geochemical study carried out in four of these centers, four major hydrothermal events have been identified: i) development of a complex prograde garnet-clinopyroxene skarn; ii) formation of a retrograde skarn and associated sulfide mineralization, characterized by two superimposed mineralization events, resulting in low-sulfidation (high-Fe sphalerite – pyrrhotite – arsenopyrite – chalcopyrite) and intermediate-sulfidation (pyrite – low-Fe sphalerite – galena – minor As-Sb-Ag tellurides and sulfides) assemblages; iii) porphyry-style mineralization consisting of quartz-molybdenite-pyrite stockwork veins and associated K-alteration that appear cutting the skarn; and iv) late barren carbonate formation as stockwork or as late vein filling. In some of the centers porphyry mineralization is overprinting the retrograde skarn assemblage and the early polymetallic mineralization, in others it is clearly overprinted by the latter. The complex relationships between the different mineralization styles at Santander are indicative of multi-stage protracted hydrothermal activity in the area. This comparative quantitative mineralogy and geochemistry study on four mineralized centers – The Santander Pipe, Blato, Puajanca and Magistrales – provides the basis for building a genetic model for the evolution of the magmatic-hydrothermal system at Santander where skarn, porphyry and polymetallic mineralization show complex relationship in space and time.

Mineralogical mapping of ore samples and the implementation of Pd and Pt measurements using Laser-Induced Breakdown Spectroscopy and µ-XRF

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Laser-Induced Breakdown Spectroscopy (LIBS) is an emerging technique in the field of analytical geochemistry. It clearly stands out for its rapidity and high sensitivity which allows the detection of trace elements up to concentrations of ppm and even ppb. This study demonstrates the use of LIBS to characterize the mineralogical content of PGEs ore samples from the Lac des Îles mine (Ontario, Canada) and to quantitatively determine their Pt and Pd contents. In this perspective, TESCAN Integrated Mineral Analyzer (TIMA) and Scanning Electron Microscopy (SEM) analyses were used to calibrate the LIBS instrument for the mineralogical characterization of PGEs ore samples whereas micro-X-ray fluorescence (µ-XRF) mapping was achieved to independently evaluate the LIBS mapping results. For Pd and Pt quantitative analyses, the LIBS instrument was calibrated with reference materials. Two rock types were scanned by LIBS for their mineralogical characterization: pyroxenite and gabbronorite. LIBS mineralogical mapping allowed the identification of four major silicate phases (chlorite, plagioclase, actinolite and hornblende) and five minor sulfide and oxide phases (Pd-bearing pentlandite, chalcopyrite, pyrrhotite, pyrite and ilmenite). Interestingly, the LIBS mineralogical maps display not only the distribution of the identified mineral phases but also their abundances along the scanned surfaces of samples. It is worth noting that the mineral phases identified by LIBS and by µ-XRF were in very good agreement for their compositions, abundances and distributions. Further, this study revealed a noteworthy potential of µ-XRF chemical mapping in identifying areas of interest for PGMs (Platinum Group Minerals). These results provide good insight for a higher-resolution characterization of PGMs within ore samples. Through LIBS mapping it was also possible to display the distribution map of Pd within pentlandite. The obtained results show the ability of LIBS to perform rapid high-resolution mapping of the mineralogical composition of PGEs ore samples. It is worth mentioning that, compared to conventional techniques, LIBS is overall significantly faster and also more sensitive to trace and light elements. Further, this study is the first of its kind allowing the establishment of calibration curves for measuring Pt and Pd contents at low concentrations up to ppm level within PGEs ore samples. These results suggest that the LIBS technique can be remarkably valuable for fast measurement of precious metals in field conditions as well as for rapid mineralogical characterization of ore samples.

Constraining the time-span of magmatic-hydrothermal activity in the Variscan belt – U-Pb LA-ICP-MS dating of skarn-related garnet from the Erzgebirge, Germany

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Europe's major Sn and W resources are hosted by magmatic-hydrothermal ore deposits of the Variscan belt: e.g. in Cornwall, the Erzgebirge, the Iberian Massif, and the French Massif Central. In the Erzgebirge, several major skarn bodies are located in the Schwarzenberg district (12 x 15 km). Although recent geochronological data relates (skarn) ore-formation to late- and post-orogenic magmatic-hydrothermal activity, details on the nature and duration of mineralization events remain insufficiently understood. In this study we present innovative in-situ LA-ICP-MS U-Pb geochronology of garnet from several skarn prospects in the Schwarzenberg district, which is complemented with available geochronological data on intrusions and mineralization in order to constrain the timing of skarn formation within the Variscan orogenic cycle. Eighteen garnet dates range from 338.2 ± 2.5 to 294 ± 8.3 Ma. Associated errors are in the range of 2.5 to 8.4 Ma, but generally tend to be <7 Ma. The oldest ages (338-331 Ma, stage I) are related to metasomatic garnets of the Globenstein skarn (n=5) – a skarn that is exceptionally enriched in W compared to the other skarn prospects in the district. Conversely, the other skarns (Antonsthal, Breitenbrunn, Hämmerlein) are younger and range from 327 to 312 Ma (stage II) and 304 to 294 Ma (stage III), respectively. Stage I and II garnets lie within the range of available zircon ages of major intrusive bodies in the area (Aue-Schwarzenberg granite suite: 334-322 Ma; Eibenstock granite: 326-311 Ma). The third stage, in contrast, does not overlap with the age of any known granite intrusions in the Schwarzenberg district. However, it coincides with widespread early Permian volcanic rocks, which presumably have intrusive roots that are not yet exposed in the Erzgebirge region. The distribution of garnet ages implies that skarn formation occurred episodically during the ~45 Ma life-time of the Variscan orogen, with the onset of magmatic-hydrothermal activity occurring significantly earlier than previously assumed – at 338 Ma, immediately after the peak of regional metamorphism. Tin and W deposits (skarn, greisen and vein-type) seem to have formed episodically over the entire 45 Ma orogenic cycle of the Erzgebirge – this is consistent with the age range of available geochronological data related to magmatic-hydrothermal ore deposits from other internal parts of the European Variscan belt.

Orogenic Gold Deposits

A New Approach to Gold Exploration Targeting in the White Gold District, West-Central Yukon Territory, Canada

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The Vertigo target of the JP Ross property is a gold mineralized showing located ~70 km south of Dawson City in the White Gold District of the west-central Yukon Territory's Yukon-Tanana Terrane. Gold-mineralized zones exhibit a strong geochemical correlation with As-Ag-Te-Pb-Bi +/- Cu-Co – a uniquely abundant suite of pathfinder elements distinct of any other Au-mineralized prospect discovered in the White Gold District to date. This study evaluates the geochemical, mineralogical, and structural parameters used to describe the Au-mineralizing controls at the Vertigo target. Petrography, electron probe microanalysis (EPMA), micro X-ray fluorescence (µXRF), and synchrotron radiation X-ray powder diffraction (SR-XRD) have defined the characteristic signatures of Au mineralization. Sample examination using optical microscopy, energy dispersive spectroscopic (EDS), and wavelength dispersive spectroscopic (WDS) EPMA has established textural relationships. µXRF analysis of sample billets has mapped the composition and element distribution of mineralized samples. SR-XRD interpretation of 126 samples has quantified mineral phases. Optical televiewer imagery (OTV) of drill holes has revealed structural geometries. Gold is hosted in a series of moderate- to high- angle, E-SE striking, S-SW dipping polyphase auriferous quartz veins and fracture sets. Associated primarily with sulphides (pyrite-arsenopyrite-galena) in magnetite-destructive quartz-sericite-chlorite +/- carbonate alteration zones, Au develops favourably in felsic- to intermediate- host rocks. Coarse visible gold occurs along fractures and in quartz veins with sulphide associations consisting of semi-massive to subhedral-euhedral arsenopyrite, subhedral-anhedral galena, and subhedral-euhedral pyrite. Analyses of gold grains suggest a close mineral association with sulphides +/- sulphosalts +/- tellurides in least altered zones. Au is accompanied by secondary sulphates, phosphates, and arsenides in most altered and oxidized zones that exhibit enriched gold grades. This study uses mineral cluster analysis to help provide an objective framework to interpret geochemistry. Cluster analysis of the 126-sample pulp aggregate analyzed using SR-XRD has classified Vertigo target lithologies, alteration types, and mineralizing styles into domains based on their diffraction patterns. Representative samples selected from each domain have been evaluated to determine the distribution of mineral species. As a direct outgrowth of this study, the supporting company (White Gold Corp.) committed to the collection and SR-XRD analysis of ~300 sample pulps across a ~100 km stretch (N-S) of properties in the White Gold District. Contextualizing the geochemical relationships observed in the White Gold District within a mineralogical framework will enhance the local and district scale understanding of ore formation and considerably improve exploration and targeting in the White Gold District.

Gold Mineralization at the Hammond Reef deposit, Atikokan, Western Ontario

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The Hammond Reef deposit owned by Agnico Eagle Mines Limited is located 170km northwest of Thunder Bay, Ontario within the Archean western Wabigoon subprovince. The deposit occurs along Marmion Shear Zone that straddles the contact between the Mesoarchean Marmion batholith and Neoarchean Diversion stock. Both intrusions are largely comprised of tonalite with minor differences in texture and modal mineralogy. It has been interpreted as an intrusion-related or orogenic gold system. The main goals of the research are to: (1) to determine the structural relationships between the veins, the shear zone, alteration and mineralization (2) to determine the absolute age of gold mineralization and, (3) to interpret how the deposit formed. To achieve this, detailed mapping, as well as re-logging of drill core was completed this past field season. Samples across high-grade zones of the deposit have been collected for geochemical and mineralogical characterization. Petrography at both optical and scanning electron microscope scales will be done on all thin sections. Based on the results, laser ablation ICP MS elemental maps of pyrite grains may be done to document the initial sitting of gold and its possible remobilization. Two samples of fine-grained tonalite and the porphyritic tonalite have been sent to the Jack Satterly Laboratory at the University of Toronto for radiometric U-Pb dating to determine the age of the host rocks and possibly mineralization. The 2021 summer field program will focus on the structural evolution of the Hammond Reef deposit with follow-up analytical work during the Fall of 2021. The result of this research will lead to a better understanding of the gold mineralization at the Hammond Reef deposit and aid in interpreting the origin of the deposit and other deposits in similar settings across the Wabigoon subprovince. This is Metal Earth contribution number MERC-ME-2021-005.

Application of Multivariate Statistical Analysis to Biogeochemical Exploration at the Monument Bay Gold Project, Manitoba, Canada

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The Monument Bay Gold Project, located in the north-west Superior Province, is a promising Archean greenstone-hosted orogenic gold deposit. In 2018, a short biogeochemical survey was conducted over the Twin Lakes Deposit, indicating a strong interrelationship between gold and its pathfinder elements with respect to the lithology. Positive results from this survey resulted in conducting wider follow-up exploration work in 2019 and 2020, covering the southern extensions of the Monument Bay property. This study aimed to identify the geochemical signature of gold and other pathfinder elements in black spruce (Picea mariana) to use as new vectors toward gold enrichment zones. To achieve this objective, 105 black spruce bark samples were collected from north of the Twin Lakes Deposit to the southern border of the property. Following sample collection and preparation, the samples underwent ultra-low detection limit analysis by ICP-MS, package VEG-ASH01 at ALS. The returned chemical analysis was treated and validated using ioGAS for basic error-checking such as censoring and winsorization. Anomalous concentrations of gold, up to 81 ppb, were detected in samples located over the Twin Lakes Deposit and toward the south of the Monument Bay property. According to the Inverse Distance Weighted (IDW) interpolation grid images, these anomalies are accompanied by high values of gold pathfinder elements (e.g., As, Bi, Pb, Sb, Se, Hg and Tl) and Co, Cr and Fe, interpreted to demonstrate a mineralogy-lithology association, representing intermediate volcanics. Furthermore, by using statistical regression techniques, the data shows that a positive correlation exists between gold and As> W> Sb> Bi> Tl> Se. Based on multivariate statistical analysis, two main factors were found to control the distribution of elements in biogeochemical samples collected at the Monument Bay Gold Project: 1) lithological-mineralogical factor indicating the presence of precious and heavy metals in biogeochemical samples located over possible concealed mineralization, and 2) physiological factor representing the essential elements for plant metabolism. Results of this work indicate a significant plant-substrate relationship was identified at Monument Bay. These biogeochemical and statistical techniques have proven to be a robust and cost-effective exploration method to identify new vectors toward gold and can be used as a valuable first-pass tool for targeting towards mineralization concealed beneath the thick cover.

Investigation of Sulphide-Poor Gold Mineralization of Kiena Deep a Zone at the Kiena Complex, Val d'Or

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The Kiena Complex, owned by Wesdome Gold Mines Ltd., is located between Val d'Or and Malartic, Québec, in the southern Abitibi Greenstone belt. Recent exploration drilling at the lower levels in the Kiena Deep A Zone intersect unusual sulphide-poor quartz vein hosted gold-rich mineralization that contrasts with the sulfide-rich mineralization in the upper Kiena Complex, particularly the S50 Zone. The gold mineralization, characterized by visible gold, is hosted by quartz veins that cut deformed ultramafic and basaltic rocks. Two distinct groups of basalt with different sources have been distinguished using lithogeochemical analyses and the distinctive basalt chemistry has the potential to be used as a marker for structural analysis. The mechanism of gold deposition, potential vectors for mineralization, and a more detailed understanding of the genesis of the mineralization are the main objectives of this study. Observations of drill core throughout the mineralized zones show that gold grade does not correlate with quartz colour, or vein thickness. Flecks of visible gold are mostly along albite fractures within the veins. A "degree of complexity" factor that considers the degree of deformation, fractures, complex mineralogy, brecciated quartz, and the presence of visible gold was generated for barren, poorly mineralized, and strongly mineralized veins. Results show that gold grade and gold grain size increase with an increasing degree of complexity within the veins. Lithogeochemical results show that the mineralized zones are associated with cryptic sodic alteration, i.e., the alteration is not observable in hand samples. This sodium alteration may be related to the albitization observed with gold mineralization in the upper Kiena Complex, where visible albite alteration is reported. There are also variations in amphibole and chlorite composition proximal and distal to mineralization that may be used as mineralization vectors. Results from this study will be used to differentiate between barren, poorly mineralized, and strongly mineralized quartz veins, aiding in mineral exploration at the Kiena Complex and other orogenic gold camps. Next steps for this project include cathodoluminescence studies of quartz, and analysis of Au:Ag and Au:Te ratios in gold grains. Understanding the genesis of sulphide-poor orogenic gold mineralization is needed to better understand local gold deposition, to generate new exploration targets at the Kiena Complex and also at other gold exploration properties.

The geochemical evolution of felsic magmatic intrusions in the Yellowknife greenstone belt, NWT: identifying adakites in the Archean

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The Yellowknife greenstone belt (YGB) hosts two historic high-grade gold deposits, the Con and Giant mines, in the Archean Slave province. Felsic magmatism began with the intrusion of the Ryan Lake Pluton (tonalites and granodiorites), the Defeat Suite and Duckfish granites, and finally host rocks were crosscut by abundant feldspar-quartz porphyry, quartz porphyry, and aplite dikes. Crosscutting field relationships between the dikes, plutons and host rocks are complicated and their relationship to each other, gold showings, or the overlying volcaniclastics of the Banting Group is unknown. The complex tectono-metamorphic history and pervasive hydrothermal alteration makes studying Archean magmatism challenging. Representative samples were taken of each lithology to compare whole rock geochemistry, focusing on the use of immobile trace elements due to the hydrothermal alteration observed. Geochemical data separate into two clusters on granite discrimination diagrams that compare Zr/TiO2 and Zr/Ti to Nb/Y. These diagrams indicate that the tonalites, granodiorites, granites, and proximal dikes are sub-alkaline and follow a fractionation trend from andesite-basalts through to rhyolites and dacites. The second data cluster are alkaline and more enriched in Nb/Y, identifying the Duckfish granite and related aplites to be trachy-andesite to trachytes. Despite the physical and petrological similarities, there are geochemical differences between two sets of aplite dikes and are associated with different plutons. The first set of aplites are proximal to the Ryan Lake Pluton and Defeat Suite and the second group of aplites are related to the Duckfish Granite. There are several tectonic discrimination diagrams that also identify at least two fractionation trends, once again geochemically separating the aplite dikes and their source. Most samples fall within the I- and S-type granite fields but the Duckfish granite and aplite samples cross between that and the A-type granite field, indicating a change in the tectonic regime. This can also be seen in discrimination diagrams that compare Ta, Yb, Nb, Y, and Rb. In each case the trends can be traced from one field to another suggesting a gradual change in the tectonic environments involved in magma generation. Finally, some samples were found to have an adakitic signature, identified by their high Sr/Y and La/Yb ratios, which has been linked to subduction of young lithosphere. The identification of these rock types in the Archean can place markers on when and where subduction and therefore plate tectonics was active in the Archean.

Field observations and structural relationships of auriferous quartz veins, Finlay-McKinlay Outcrop, southern Lynn Lake Greenstone Belt, Trans-Hudson Orogen, Manitoba

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The Lynn Lake Greenstone Belt (LLGB) in the Paleoproterozoic Trans-Hudson Orogen (northern Manitoba) is divided into two east-west trending volcanic belts separated by felsic intrusive rocks. The LLGB has had a rich exploration and mining history for gold and base metals, and hosts several orogenic gold deposits including the old MacLellan, Farley Lake, and Burnt Timber mines. Ongoing exploration in the region by Alamos Gold Incorporated has recently focused on the Finlay-McKinlay Outcrop (FMO) which lies within the southern section of the LLGB. The FMO consists of a quartz vein-bearing medium grained quartz diorite, and the veins are believed to host potentially economic quantities of gold. The aim of this project is to develop a better understanding of the evolution of the rocks and veins in the Finlay-McKinlay outcrop and their relationship to the overall development of the LLGB and other gold deposits in the area. The quartz diorite in the FMO intrudes the southern belt of the LLGB which is composed of tholeiitic to calc-alkaline metavolcanic and metavolcaniclastic rocks (Wasekwan Group). Sickle Group siliciclastic rocks unconformably overlie these rocks to the south. Initial field work undertaken during the 2020 summer season was the collection of 273 structural measurements which include orientation of foliation, shear zones, and quartz veins and the creation of a 1:20 scale map of the outcrop. In general, the quartz veins strike to the NE-SW and have a steep dip ranging from 75-90 degrees to the NW. Many have irregular shapes, and pinch and swell along strike. Alteration halos in the host diorite extend up to 6 cm on either side of the quartz veins. These halos show an increase in minerals such as biotite, tourmaline, chlorite, and carbonate. The general trend of the orthogonal joints is similar to the quartz veins suggesting a possible relationship between the presence of the joint sets and the formation of the veins. Shear zones also trend NE-SW and are more common towards the contact with the Sickle Group conglomerate to the south. Representative oriented, polished thin sections, and whole rock lithogeochemical samples have been obtained and will be examined to determine the paragenesis of vein and alteration minerals relative to structures and metamorphism, and to provide constraints on the origin and the effects of interaction with hydrothermal fluids during vein formation.

A new look at the Troilus Au-Cu project in the Frotêt-Evans greenstone belt, Quebec

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The Troilus Gold Project located in the Frotêt-Evans greenstone belt (FEGB) of central Quebec includes the past-producing open pit Troilus Cu-Au Mine with historical Au production of over 2 Moz and 70,000 tonnes of Cu between 1996 and 2010. The FEGB is composed of variably metamorphosed mafic to ultramafic volcanic and sedimentary rocks with multiple mineralizing styles that exhibit economically significant grades of Au, Ag, and Cu. Current brownfields and greenfields exploration work at the Troilus Gold Project is being conducted by Troilus Gold Corp. Diamond drilling at the newly discovered Southwest (SW) zone, in addition to main ore bodies J4 and Z87, has significantly expanded Troilus' resource estimate since drilling commenced in 2018. A mineral resource estimate published in July 2020 increased the indicated resources to 4.96 Moz AuEq at an average grade of 0.87 g/t and further increased the inferred resources to 3.15 Moz AuEq at 0.84 g/t. Recent exploration and prospecting on the 107,326 hectare property has identified three additional high-grade gold zones, the: (1) Beyan; (2) Testard; and (3) Goldfield Boulders. Collaboration between Troilus and Western University aims to advance the metallogenic interpretation of the FEGB. This study aims to elucidate the genesis of ore formation and mineralizing extent of the past producing Troilus Mine. Petrography, electron probe microanalysis (EPMA), X-ray diffraction (XRD), X-ray fluorescence (XRF), and fluid inclusion studies performed at Western University will assist the company in determining the geochemical, lithological, alteration, and structural controls on ore formation. Located in an under-explored region, the Frotêt-Evans greenstone belt has seen relatively limited scientific research. Past studies on the Troilus deposit have produced conflicting Au deposit models, which presents a gap in the literature in need of addressing. Initial petrography and EPMA of the main zone reveal two Au-mineralizing styles, both associated with quartz-carbonate veins: (1) free Au located in vein material without sulphides present; and (2) free Au grains associated in fractures within sulphides, namely sphalerite, chalcopyrite, chalcocite +/- pyrite, pyrrhotite, and galena. Au occurs primarily as native Au and electrum but is also found with associated Ag-tellurides, Bi-selenides and native Bi. Geochemical relationships observed at the SW zone have introduced an Au-As association. Analysis of samples retrieved from this new discovery contextualized with established interpretations from the main zone will provide insight into the broader ore forming controls at the Troilus Mine.

Geomechanical process simulation - 3D mapping of fluid-flow and tectonic deformation in the Superior province

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Lode gold deposits are often structurally controlled and found in the transition zone representing the boundary between brittle and ductile domains at the base of the seismogenic crust. Disseminated to massive lode hosted gold mineralization is often trapped in (1) fault zones, (2) fold hinges in either massive or disseminated form, or (3) permeable rock types such as conglomerates. In addition, chemically reactive contacts with banded iron formations (BIFs) help with gold localization together with distinct precursor alteration zones. Given these premises, the goal of this study is to investigate, model and predict the influence of structural settings (geometry) and associated physical parameters on the gold deposit's distribution, to assist mineral exploration. Open source numerical modelling software OpenGeoSys, has been used to reconstruct the major fault zones at a crustal scale (52 km long * 20 km wide) in the Malartic mining district. The synthetic model with detailed geological conditions has been used to represent the distinction between the thermal convection fluid flow models and deformation induced fluid flow models in 3D. Preliminary benchmark models were extended to craton scale models (174 km * 75 km) in a cloud computation environment to facilitate parallel processing. Our results demonstrate that the consideration of faults in 3D finite element models for coupled fluid and heat transport simulations on different scales have the potential of indicating new favourable areas, where gold mineralization might be located. Key, initial results of OpenGeoSys models of the physical parameters of the wall rock along faults or intrusions might have strong correlation with the gold deposition, which can be used in a predictive way to identify areas of favourable ground for discovery of gold deposits. This is Metal Earth Publication No. MERC-ME-2021-016.

Geophysics

Constraining depth-imaging of the Lombador VMS deposit (Portugal) through 3D forward modeling, cross-dip analysis and tomographic inversion

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Seismic methods have started to provide an affordable way of studying the subsurface for resource exploration. In recent decades, the method has been used more often as an effective way of deep-targeting and providing reliable sensitivity beyond what other geophysical methods are able to (e.g., > 500 m). In early 2019 within the frame of the H2020-funded Smart Exploration project, and with the objective of testing new technologies for mineral exploration in highly challenging mining areas, a seismic survey was conducted at the Neves-Corvo mine, south Portugal. The seismic acquisition consisted of two 2D seismic profiles acquired on the surface above the known tier-1 Lombador deposit and four seismic profiles deployed inside mine tunnels located approximately 600 m below the surface profiles. A novel approach here was to acquire both surface and tunnel seismic datasets simultaneously through a dedicated GPS-time transmitter also developed within the project. This helped to better illuminate the target and also allowed to provide a background velocity model between the surface and the tunnel lines. While in a highly noisy mining environment with an active raise boring happening next to one of the tunnel profiles, reasonable quality data were acquired and the processing work had to address this relatively noisy dataset. Through a tailored processing workflow, reflections interpreted to originate from lithological contacts and the Lombador deposit were imaged. These interpretations were validated using 3D exploding reflector modelling via raytracing and a pseudo-3D cross-dip analysis. The shots generated inside the exploration tunnels and recorded on the surface allowed a unique opportunity for estimating P-wave traveltimes and velocities between the tunnel and the surface profiles, these were used in a traveltime tomographic inversion to guide time-to-depth conversion and better positioning of the reflections. A low-velocity zone on the southern portion of the surface profile was also inferred to be caused by lithological contacts or a fault system.

Deep-targeting of the iron-oxide deposits and their host-rock structures using 3D reflection seismic data and machine learning algorithm

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Increased iron ore price on the market has renewed investments in the exploration. Parts of this might be due to capital investment in infrastructures and parts due to push toward green technologies requiring more ferrous and nonferrous minerals to be available. Sweden as the biggest producer of iron ore in Europe conducts many geophysical and geological studies at both active and historical mining areas. However, these studies are mainly limited to drilling and electromagnetic surveys typically done airborne. Our study area is located in south-central Sweden at the historical mining site of Blötberget within the so-called Ludvika Mines and it is known for its high-quality iron-oxide mineralization and the foundation of many Swedish major industries such as ABB (ASEA Brown Boveri). Since there was a particular interest in targeting and delineating deeper parts of the known mineralization and possible additional resources at depth, a reflection seismic survey was deemed necessary and carried out. These surveys, began in 2015, were conducted in a systematic approach from downhole logging to 2D trials before conducting a sparse 3D survey in 2019. Here, we focus primarily on the 3D dataset and how it was planned and executed as well as providing information on the data processing results. In a novel approach, high-amplitude reflections were tied to borehole data and used to estimate where potential additional resources are possible both vertically and laterally. This helped to provide an estimate of approximately 10 Mt additional resources at depth worth drilling for detailed assessments. Reflections related to major faults were also imaged helping to better understand the tectonic frameworks at which the deposits are currently configured. To maximize the value of the 3D seismic dataset, we are currently extracting subtle information from the volume using pattern recognition and machine learning algorithms. This study encourages using seismic methods more often than used for deep exploration and mine planning, in particular in Sweden but also elsewhere.

E-vib as an innovative seismic source in hard rock mineral exploration in Ludvika Mines (Sweden)

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The increasing consumption of raw materials worldwide, produced by society and the development of green-energies, requires research on innovative technology in mineral exploration that leads to enhanced targeting imaging thus solutions for sustainable exploration in the mining industry. Cost-effective solutions for raw material exploration is the aftermath of vanguard and well-produced ideas. For this reason, a prototype E-vib (electromagnetic based, electrically driven) broadband seismic vibrator was upgraded and developed for hard rock and mineral exploration seismic surveys, and tested in the Ludvika Mines of central Sweden, to contribute to innovative mineral exploration. The data acquisition was carried out with 550 receivers, and the E-vib, as a seismic source, operated in a frequency range of 2 to 180 Hz, using a linear sweep and a peak force of 7 kN, in order to obtain a fixed 2D seismic profile of about 2.7 km length. Crucial processing steps and the broadband signal nature produced by the E-vib suggest reflections related to the iron-oxide mineralization, and a main crosscutting reflection that might be part of a geological fault system. The broadband source and processing improved the seismic resolution when compared with previous seismic datasets from the area, which involved other types of sources, e.g. drophammer. Those improvements in the seismic data were reflected on the target imaging resolution, and signal-to-noise ratio corresponding to previous datasets from the same area. The extracted wavelet of the P-wave arrivals revealed the advantage of a broadband data, originated by the electromagnetic vibrator (E-vib), and processing when compared with previous seismic datasets. Our results highlight the potential of electronic seismic vibrators as a seismic source and open up new possibilities for the E-vib with its processing workflow to enhance mineral ore bodies as targets in hard rock environments.

Evidence of Pacific Plate subduction beneath Haida Gwaii, western Canada

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In 2012, a Mw 7.8 earthquake occurred off the coast of Haida Gwaii, a group of islands in western Canada, that caused a 13m high tsunami. In this region, there is a poorly defined triple junction of the Pacific Plate, the North American Plate and the Explorer Microplate. The 2012 Haida Gwaii earthquake had a thrust mechanism, indicating that the Pacific Plate may be subducting beneath North America. Past studies have observed a dipping structure beneath Haida Gwaii; however, its landward extent is unresolved. In this study, we calculate teleseismic receiver functions using data from a set of seismic stations larger than any previous study, including receivers on the mainland. Analysis of the receiver functions show a back-azimuth dependent variation in signal amplitude and arrival times as well as changes in polarity on the transverse component, features that are associated with dipping structures. There appears to be a signal identifying a low-velocity layer in receiver functions in the vicinity of Haida Gwaii and extending as far as the eastern edge of the Hecate Strait that separates the islands from the mainland. Identifying this low-velocity layer adds to the body of evidence that the Pacific Plate is subducting beneath the North American Plate. The absence of the low velocity layer at mainland stations indicates that the oceanic plate does not subduct this far. From these results, we can provide new constraints on the amount of time that subduction has taken place, allowing for better understanding of the evolution of this tectonic boundary. We can also better estimate the depth of subduction and constrain the location of future deep thrust earthquakes. Evidence of subduction beneath Haida Gwaii will allow for updates to be made to building codes, earthquake and tsunami preparedness and tsunami warning systems in British Columbia.

Other

The tectonic setting and mineralization potential for nickel scandium, chromium and cobalt of ultramafic complexes in NE Queensland

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North-eastern Queensland has significant exploration potential for many critical metals; resources that are considered crucial for the development and sustenance of new technologies in the future. Mafic-ultramafic complexes, such as those in northeastern Queensland, are highly prospective for numerous critical metals, but are poorly characterised and understood, and have received very little exploration attention despite their potential. The project aims to investigate ultramafic rocks in northeastern Queensland, focussing on their tectonic setting, character, distribution, genesis and potential to host critical metals including nickel, scandium, chromium and cobalt mineralisation. Numerous occurrences of ultramafic rocks have been documented across northeastern Queensland, including at Greenvale, Cowley, Port Douglas and more recently at Running River. The ultramafic complexes typically comprise serpentine-talc-carbonate schists, gabbros, pyroxenites and anthophyllite/cummingtonite schists bearing significant chromite mineralization. Nickel carbonate mineralization has been observed across the study sites and is likely indicative of nickel mobilization out of olivine. This process is critical in the development of economic nickel rich laterites. Due to its resistance to alteration, in the absence of other primary phases, chromite chemistry can be used as a robust petrogenetic indicator to fingerprint the tectonic setting and genesis of serpentinized peridotite, and will be critical in delineating the tectonic settings and origins of ultramafic complexes in this study. Additionally, quartzite and gneissic units of the Running River metamorphic rocks, associated with chromite rich ultramafic pods, comprise rare 1-3mm sized garnet grains bearing oriented rutile needles – a feature often observed in HP-UHP metamorphic rocks that have undergone decompression and TiO2 exsolution. The garnets also contain rare inclusions of quartz displaying radial decompression fracture patterns potentially indicative of coesite. Early P-T work using garnet only and garnet-biotite thermobarometry has yielded results of approximately 12 kbar and 800 degrees Celsius. However, the mineral assemblage and unusual garnet chemistry (almandine-spessartine rich) likely indicate retrograde conditions suggesting that the peak metamorphic grade is likely much higher. Constraining the P-T conditions of these garnets will be crucial in understanding the tectonic history of both the economically significant ultramafic rocks and broader northeast Queensland.

Arc-Front Volcanic Centers and Hydrothermal Systems along the Monowai Segment, Tonga-Kermadec Arc, SW Pacific

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Three significant active hydrothermal systems have been found at arc-front volcanoes along the Monowai Segment of the Tonga-Kermadec arc. Most occur in summit calderas of still active volcanic cones and exhibit different characteristics (e.g., high- vs low-temperature venting, boiling, magmatic contributions to the hydrothermal system) depending on the settings. Volcano 18 at 24°30'S contains a stratovolcano (10 km diameter, rising to 190 mbsl) with >40 small cones cutting the stratovolcano along a SW-NE lineament and another stratovolcano (14 km diameter) dominated by a 6.9 x 6.3 caldera (1520 deep). The eastern wall of the caldera has clusters of chimneys, including two black smokers (260°C), sulphides, and mussels present. Volcano 19 at 24°48'S is a 14 x 12 km stratovolcano rising from 1400 mbsl to 385 mbsl, containing an elongated caldera (1.9 km diameter). It contains two large (800 x 800 m) hydrothermal fields; the summit of the central cone and a swarm of dykes in the southern wall of the caldera. Hydrothermal vents at the summit of the cone include sulphide chimneys venting phase-separated hydrothermal fluids (270°C). Contrasting the arc-front volcanoes occupying the shallowest parts of the volcanic arc, the Monowai volcanic center (25°53'S), occupies a deep depression (Monowai Rift Graben) crossing the arc front. The volcanic complex consists of a large caldera complex (12 km wide, 1600 m deep) and adjacent stratovolcano (Monowai Cone) rising nearly to sea level. Significant hydrothermal activity is located along the southwest caldera wall (Mussel Ridge) with low-temperature (>60°C) hydrothermal venting and inactive sulphides obscured by large mussel beds. A major control on venting along the arc front is water depth (900 m at Volcano 19 to over 1600 m at Monowai caldera), with the highest temperatures inferred for the deep vents and significant volcanic degassing at the shallow vents. We have mapped the volcanic centres to characterize the volcanic stratigraphy associated with the different styles of hydrothermal venting. These comparisons provide important clues for recognizing potential ore-hosting volcanic caldera sequences and structures in ancient submarine volcanic arcs. This is Metal Earth Contribution MERC-ME-2021-018.

Defining the metamorphic architecture of the Onaman-Tashota greenstone belt in mafic volcanic rocks, eastern Wabigoon subprovince, Ontario

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The Onaman-Tashota greenstone belt (OTGB) of the eastern Wabigoon subprovince is a Meso- to Neoarchean volcano-sedimentary succession ranging in metamorphic grade from greenschist to amphibolite facies. It is bounded to the north and south by the metasedimentary English River (ERS) and Quetico subprovinces, respectively, which are generally of higher metamorphic grade, ranging from amphibolite to granulite facies. We utilize the spatial and temporal distribution of peak metamorphic mineral assemblages and their relationship to structural features across the OTGB in attempts to distinguish between regional and contact metamorphic events and explain its current-day metamorphic grade distribution. Mineral assemblages in mafic metavolcanic rocks near the southern and central portion of the belt are transitional between the greenschist and amphibolite facies, and predominantly consist of actinolite + magnesio- to ferro-hornblende + albite-andesine + chlorite + epidote-clinozoisite + quartz + titanite ± ilmenite ± calcite ± pyrite ± pyrrhotite ± chalcopyrite. These assemblages change to magnesio- and ferro-hornblende + oligoclase-bytownite ± anorthite + quartz + ilmenite ± cummingtonite-grunerite ± pyrite ± pyrrhotite regionally towards the north of the belt, and locally adjacent to the Jackson pluton at the center of the belt. Also adjacent to the pluton, altered pillow selvages contain garnet + gedrite-ferrogedrite + biotite + ilmenite + anorthite + apatite. These observations suggest an increase in grade to the amphibolite facies regionally at the north of the greenstone belt, and locally as contact metamorphism against the Jackson pluton. Metamorphic minerals generally define the regional S_1 foliation, but are observed to overgrow the fabric where grade increases to the amphibolite facies, placing a time constraint on the regional D_1 deformation to be pre- to syn-2684 Ma, the same age as the Jackson pluton. Two late belt-scale shear zones crosscut the OTGB where mineral assemblages transition to contain chlorite + quartz + albite + calcite + ilmenite ± oligoclase ± rutile ± magnetite ± biotite ± muscovite ± pyrite ± chalcopyrite ± sphalerite, suggesting retrograde metamorphism to greenschist facies due to shear zone activity. Metamorphism in the OTGB is largely influenced by contact metamorphism surrounding late felsic plutons, and retrograde metamorphism to the greenschist facies due to shear zone development. Future work will consider the effects of regional metamorphism accompanying the subprovince collision against the ERS in both mafic and metasedimentary rocks. This is a Metal Earth contribution publication number MERC-ME-2021-004.

Geology of the North Fiji Basin Triple Junction: A possible modern analog of late Archean mafic magmatism and VMS formation

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The North Fiji Basin Triple Junction (NFBTJ) is located at the center of the world's largest and most evolved backarc basin. The NFBTJ is a ridge-ridge-ridge (RRR)-type triple junction where the New Hebrides, Balmoral Reef and Conway Reef microplates meet. NFBTJ exists in its current configuration since 1 Ma. A compilation of marine geophysical data (hydroacoustics, magnetics, and gravity) was used to construct the first comprehensive geological map of the NFBTJ at 1:250,000 and investigates the relationship between the mapped structure, magmatism and hydrothermal systems. Because the triple junction has acted as a locus for high-heat flow, faulting, and crustal-scale permeability for more than 3 million years, there is a close link to the evolution of regional hydrothermal activity. However, hydrothermal vents have only been reported from the southern arm of the NFBTJ. Here, we compare mapped formations (i.e., the sequence of depositional events, the composition of the substrate, and its deformation and structures) to the location of known hydrothermal vents and assess the geological, geodynamic, and structural differences between the arms of the triple junction to identify optimal conditions promoting hydrothermal venting. The northwest arm (N160) is a broad 30-km wide zone of normal faulting with volumetrically minor older eruptions along the axial rift graben. The northeast arm (N55) is a 30-km wide, short 57-km long rift graben that terminates at a strike-slip zone. The southern arm (N120) is a well-developed spreading ridge and contains most of the central volcanic complex (27-km long, 15-km wide, and 0.4-km max-height). Numerous hydrothermal systems (White Lady, StarmerII, Pere Lachasise and Sonne99) and their associated sulphide occurrences are located within the N120 arm, adjacent to the central volcanic complex. Between 3 and 1 Ma, the N55 graben evolved from a strike-slip fault that intersected the N160 and N120 arms junction, allowing for high permeability through faults and magmatic influences from N120. N55 arm is now developing a spreading center similar to the N120 arm, with increasing magmatic input in response to readjustment due to the North Fiji Fracture Zone. Thus, N55 is likely to become a new center of hydrothermal activity as the microplates adjust. The N160 arm shows no evidence of active magmatism, and all extension is interpreted as tectonically controlled. This is Metal Earth publication number MERC-ME-2021-021.

Intrabasinal sediments and tectonostratigraphy of the Lau Basin: Assessing linear vs. diachronous models for the opening of the Lau back-arc

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The Lau Basin in the southwest Pacific Ocean is a typical example of a back-arc basin that is actively extending due to trench rollback and microplate rotation. Extension is partially accommodated by the opening of many small volcano-sedimentary basins, individually 2 - 40 km long and 1 - 45 km wide but collectively spanning the entire 400 km width of the Lau back-arc. However, the nature, timing and controls of sub-basin opening are not well understood. Here, we investigate the sedimentary and structural history of sub-basin development in a 290-km long, east-west transect at 17°20’S. To analyze the sediment stratigraphy in each sub-basin, we use high-resolution, 0.5–6.0-kHz sub-bottom profiles collected with the ‘ATLAS Parasound’ system during mapping aboard R/V Sonne (SO267). Reflection seismics from the same cruise reveal the large basin-bounding structures, such as regional faults at scales of kilometers, while the Parasound data reveals sedimentary structures and textures, in addition to smaller, localized faults and buried ridges at a resolution of a few meters. The structures, sedimentary units and volcanic features were analyzed in 24 sub-basins along the 290-km long transect. The individual basins have an average width of 6 km and an average sediment thickness of 50 m, comprising mostly volcaniclastic material and minor pelagic sediment. The sub-basins were divided into five groups based on sedimentary composition and structures, and the type of underlying crust, each representative of a different phase of basin opening. Normal faulting dominates, with evidence that some might have provided sub-seafloor pathways for magma or hydrothermal fluids. The results show that extension did not occur uniformly from the center of the basin; rather, the locus of extension jumped to different parts of the basin over time. We propose a model of mainly diachronous opening of the basin and asymmetric versus linear extension, which has important implications for the development of crustal permeability and magmatism during back-arc spreading. The ability to recognize this extensional style has important implications for understanding crustal permeability and magmatism in ancient greenstone belts, including distributed versus focused extension and consequences for the location of ore deposits. This is Metal Earth Contribution No. MERC-ME-2021-023.

Magmatism in the Eocene Emigrant Pass volcanic field, northern Nevada: trace element and isotopic indicators of magma sources and crustal influences

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The Emigrant Pass Volcanic Field is a part of the Eocene igneous activity associated with continental arc volcanism in northern Nevada, western United States. The aim of this project is to use whole-rock major elements, trace elements, and the isotopic compositions of lead, hafnium, strontium and neodymium to determine the magma source(s) of this volcanic suite and establish if crustal contamination is important in petrogenesis. The Emigrant Pass Volcanic Field falls within the economically-important Carlin Gold Trend and has been studied for a relationship between the origin and magmatism of the volcanic field with the deposition of the Carlin-Trend gold. The isotopic analysis will provide indications of the mantle sources of the mafic volcanic rocks and the magmatic evolutionary relationship between the mafic and felsic rocks. The Emigrant Pass suite is also important in that it falls within the transition zone between Phanerozoic accreted terrane basement to the west and Precambrian basement to the east, and isotopic compositions will indicate which of the two basement terranes influences magma chemistry. The volcanic rocks sampled for this study are from four units: Primeaux Lava Sequence (38.3–38.1 Ma), Mack Creek Lava Sequence (38.4-37.1), the Bob Creek lava dome (37.7 Ma), and late porphyritic dykes (36.7-36.4 Ma). The Emigrant Pass igneous rocks range from basaltic andesite to rhyolite in composition. Major mineral phases include plagioclase, hornblende, quartz, biotite, and pyroxene. All of the lavas and intrusive rocks have normalized incompatible element patterns typical of subduction-related magmas, like other Eocene lava sequences in the northern Great Basin (e.g., Fish Creek Mountains). Initial isotope ratios are: $^{87}Sr/^{86}Sr$ = 0.705143 to 0.707914, $^{143}Nd/^{144}Nd$ = 0.512122 to 0.512420 (εNd = -3.3 to -9.2), $^{176}Hf/^{177}Hf$ = 0.282393 to 0.282610 (εHf = -5.4 to -13.1), and $^{208}Pb/^{204}Pb$ = 38.9401 to 39.2212. The basaltic andesites have the lowest Sr and Pb, and highest Nd and Hf isotope ratios, and the primary magma source appear to be Phanerozoic lithospheric mantle ($^{87}Sr/^{86}Sr$ < 0.706). The evolved magmas show strong correlations between trace elements (e.g., Th/La) and isotopic ratios with increasing SiO_2 content, and crustal contamination is a major process in magma evolution. The crustal component in the felsic lavas has highly negative εNd and εHf that may indicate a Precambrian crustal source. Based on this study and work at nearby Eocene volcanic centres, the Phanerozoic-Precambrian transition zone appears to include mantle and crustal components of varying ages that are structurally interleaved.

Microplate interactions and hydrothermal activity at the Mangatolu Triple Junction, Northern Lau Basin

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The Mangatolu Triple Junction (MTJ), located in the northeast Lau Basin in the southwest Pacific, consists of three spreading centers that intersected in a ridge-ridge-ridge (RRR)-type configuration in the last 500,000 years. The northern part of the Lau Basin is dominated by a complex microplate mosaic, with three of the plates meeting at the MTJ. At least three distinct active hydrothermal systems are identified by plumes detected in the water column, at the center of the triple junction, at a large central volcanic complex coincident with the axis of the northeastern arm, and on an off-axis volcanic complex of the southern arm. A compilation of marine geophysical data (hydroacoustics, magnetics, and gravity) was used to construct the first comprehensive geological map of the MTJ at a scale of 1:200,000 to investigate the relationship between the mapped structure and magmatism and the known hydrothermal vents. Analysis of the geological map shows three stages of back-arc crust development, with the most crustal growth since the initiation of the MTJ in the northeastern arm, followed by the southern and western arm, which are in transition between rifting and magmatic spreading. The three hydrothermal systems are closely spatially associated with volcanic ridges (approx. 1100 m x 300 m x 30 m), most likely underlain by dike-like intrusions at the spreading center. Additionally, the vent sites inside the neovolcanic zone are proximal to large shield-like volcanic complexes (approx. 22.5 km x 6.5 km x 200 m high) and vent sites outside the neovolcanic zone are related to off-axis fissure volcanoes of the southern arm (approx. 17.5 km x 4 km x 650 m high). Furthermore, the hydrothermal vents are located in areas where high fault density, coincident with enhanced magmatic activity at the volcanic centers transitions into lower fault density. The distribution of hydrothermal venting shows the importance of large-scale permeability, in combination with structurally localized magmatism, which can be directly linked to the evolving microplate mosaic in the NE Lau Basin. The results of this study contribute to our growing understanding of the role of triple junctions in microplate formation and the initiation of hydrothermal systems in back-arc basins.

Zircon chemistry, Dizon porphyry Cu-Au deposit, Philippines

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The Dizon porphyry Cu-Au deposit (0.67 Mt Cu, 140 t Au) is located 15 km south of the present summit of Mount Pinatubo in the Philippines. Porphyritic andesite and diorite intrusions host the deposit and are linked to the mineralization at 2.5 Ma. It has been suggested that zircon trace element composition may be used to evaluate the fertility of magmas, and potentially identify rocks hosting porphyry-type deposits. This study evaluates zircon geochemical signatures at Dizon. Our previous work based on amphibole and oxides shows that the parental magmas were oxidised, >FMQ+2, and hydrous, 5 wt%. The values are similar to those for host rocks associated with porphyry Cu deposits around the world. Zircon grains were separated from andesite porphyry for trace element analysis using LA-ICP-MS. Zircon grains show oscillatory zoning in CL images due to varying U and Th, and the ratios of Th/U range from 0.32 to 0.85 (av 0.55), confirming magmatic origin. U/Yb ratios are moderate, 0.38, confirming little input of crustal material. Chondrite-normalized plots of REEs of zircon give a steeply sloped positive curve with low LREE and MREE, and high HREE. They show positive Ce anomalies, Ce/Ce* (CeN/[NdN2/SmN]) ranging from 5 to 125 (average 56), and moderate Eu anomalies, Eu/Eu* (EuN/[SmN*GdN]1/2) between 0.39 and 0.67 (average 0.54). Eu anomalies > 0.3 are consistent with zircon crystallization in hydrous magmas, where suppression of early plagioclase crystallization occurs. Ti-in-zircon thermometry yields an average temperature of 762°C. Zircon saturation temperature calculated using bulk rock composition is 758°C, suggesting the crystallization of zircon at near constant temperatures. The Ce/Ce* anomaly and Eu/Eu* anomaly of zircon at Dizon are similar to those from other large porphyry Cu deposits, such as El Teniente, Chile (Ce/Ce*=54, Eu/Eu*=0.52) and Dexing, China (Ce/Ce*=34, Eu/Eu*=0.43).

Geochemical variation of magmatic oxide-apatite mineralization associated with AMCG suites: insights on petrography and mineral chemistry for the Lac à Original area, Quebec

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Magmatic oxide-apatite mineralization is spatially and temporally associated with Proterozoic massif-type anorthosites, providing important resources for Ti (hemo-ilmenite: $FeTi_2O_4$), V (magnetite: Fe_3O_4) and P (apatite: $Ca_5(PO_4)_3(OH,F,Cl)$). For example, the Lac Tio mine in Quebec, the world's largest producer of TiO_2, is a hemo-ilmenite rich-norite deposit within an andesine anorthosite occurrence. However, the origin and genetic relationship of both the anorthosite host- and oxide-apatite mineralization are still highly debated, as well as the exact tectonic setting. Variation in the oxide mineralogy (Ti-magnetite, ilmenite, hemo-ilmenite) appears to depend on the type of massif anorthosite (labradorite or andesine composition of plagioclase) which may relate to different parental melts and/or degrees of crustal contamination, leading to an increase of fO_2, during emplacement of plagioclase rich-mushes into the crust. In the Grenville Province, Quebec, the oxide mineralogy changes as a function of the anorthosite age: andesine-type anorthosite that are younger than 1100Ma are orthopyroxene-bearing and host hemo-ilmenite mineralization, denoting higher degrees of contamination than labradorite-type anorthosites that are older than 1100Ma, olivine-bearing and host Ti-magnetite mineralization. This previous work is part of a PhD research in which the aim is to improve our understanding of what causes these changes by studying the geochemical variation of different oxide-apatite mineralization in the region of Saguenay-Lac Saint Jean, Quebec, where 4 different ages of anorthosite exist. In this study, we focus on describing the mineralogical and geochemical variation (whole-rock and mineral chemistry) with stratigraphic depth of the Lac à Orignal Ti-P occurrence, which represents a ferrogabbro/apatite-norite unit, (50-70m thick with average of 5.5% P_2O_5) with approximately 25% Fe-Ti oxides and 8-15% apatite, hosted within a 1080Ma andesine-type anorthosite. Sampling within different depths possibly to identify a variation in the oxide mineralogy from Hm-ilmenite + Magnetite to Magnetite + Ilmenite inwards the intrusion. This provides us an opportunity to evaluate the role of fractional crystallization, magma dynamics and assimilation of crustal rocks in forming Ti-P deposits in anorthosite massifs.

Evidence of microbially influenced sulfur cycling in seafloor massive sulfide deposits from the Juan de Fuca Ridge

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The Juan de Fuca Ridge (JdFR) is an intermediate-rate spreading center located off the coast of Vancouver Island and the Pacific Northwestern United States that hosts both sedimented and sediment-free hydrothermal systems (Middle Valley and Axial Volcano, respectively). Middle Valley, which is overlain by up to 2 km of Pleistocene turbiditic sediments, hosts one of the largest known seafloor massive sulfide (SMS) deposits. Significant accumulation of permeable sediments at mid-ocean ridges allows for increased seawater infiltration and subsurface mixing with ascending hydrothermal fluids, which can lead to significant subseafloor mineral precipitation and the formation of relatively large SMS deposits such as the deposit at Middle Valley. In contrast, limited permeability and related subseafloor fluid mixing at sediment-free basalt-hosted mid-ocean ridge hydrothermal systems, such as Axial Volcano, results in a large percentage of hydrothermally mobilized metals venting and dispersing into the water column. The Endeavour vent field, which is also located on the JdFR, occurs at the outermost extent of turbiditic sedimentation, and evidence from vent fluid chemistry suggests the presence of organic carbon containing buried sediment beneath the currently sediment-free basalt flows. In this study, we use multiple S isotope ratios of hydrothermal precipitates from Middle Valley, Axial Volcano, and Endeavour to isotopically fingerprint differences in hydrothermal S cycling associated with sedimented and sediment-free substrates. We present a three-component mixing model in Δ33S and δ34S space that represents the differing contributions of S derived from seawater, magmatic sources, and both sediment and crustal S sources that have been influenced by microbial activity at the three sites. Our model indicates that microbial influence on hydrothermal S cycling and related SMS deposit formation along the JdFR may be more significant than was initially hypothesized for both the sedimented and sediment-free sites due to the systematic removal of light S isotopes from these hydrothermal systems during microbial sulfate reduction (MSR). These data imply that MSR may be an underrepresented process affecting hydrothermal sulfide mineralization along the JdFR. Our results reveal that multiple S isotope analyses may be an important tool for identifying organic-rich substrata and potentially related large SMS deposits underlying mid-ocean ridge hydrothermal vent systems.

High pressure amphibole and phengite record deformation during exhumation, Evia, Greece

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Southern Evia in Greece exposes an inverted high pressure-low temperature (HP-LT) metamorphic sequence that has been loosely correlated with the Cycladic Blueschist Unit (CBU). On the island, the CBU is divided into the metavolcanic and ophiolitic Ochi Nappe and predominantly metacarbonate Styra Nappe. A lower-grade unit, the Almyropotamos Nappe, is exposed in the core of a N-S trending antiform and comprises Eocene platform carbonates overlain by metaflysch. The Almyropotamos Nappe occupies a tectonic window defined by the Evia Thrust, a brittle-ductile fault zone that emplaced the Ochi and Styra nappes atop the Almyropotamos Nappe. New multiple single-grain white mica total fusion $^{40}Ar/^{39}Ar$ ages indicate that deformation occurred along the Evia Thrust at 25-23 Ma. White mica $^{40}Ar/^{39}Ar$ data on either side of the tectonic window record Eocene dates between 40 and 32 Ma, broadly coinciding with estimates for the timing of NE-directed thrusting of the Ochi Nappe over the Styra Nappe. Strain associated with thrusting localized as cylindrical folds in Styra marbles, with fold axes parallel to the stretching lineation and a clear strain gradient increasing toward the upper contact with the Ochi Nappe. The Ochi Nappe displays a strong L-S fabric defined by acicular blue amphibole and type-3 refold structures with fold axes trending parallel to the NE-SW oriented stretching lineation. Whereas the Ochi Nappe is the only unit on Evia that preserves peak blueschist facies mineral assemblages, both the Almyropotamos and Styra nappes display evidence for retrogressed initial HP-LT assemblages. Isochemical phase diagrams calculated in the Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2±O_2 system support minimum peak metamorphic conditions of 12.5 ± 1.5 kbar and 465 ± 75 °C for an Ochi Nappe blueschist, and 6.0 ± 0.5 kbar and 315 ± 15 °C for an albite mica schist from the Evia Thrust. Peak P-T conditions for the Ochi Nappe align better with those of the Lower Cycladic Blueschist Nappe, indicating that the section of the CBU exposed on Evia lies below the Trans-Cycladic Thrust. The Early Miocene ages from the Evia Thrust overlap with the proposed timing for the initiation of bivergent greenschist facies extension in the Cyclades, whereas the remainder of the region uniformly records older Eocene deformation ages. The similarity in $^{40}Ar/^{39}Ar$ ages across the tectonic window contrasts with age relationships observed in similar tectonic packages on Lavrion and suggests that regional-scale deformation persisted until the Late Eocene before strain became localized along brittle-ductile corridors by the Early Miocene.

LA-ICP-MS U-PB geochronology of carbonates from Ag-Bi-Co-Ni-As±U veins in the Erzgebirge (Germany and Czech Republic): New insights into the timing of mineralization

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Hydrothermal Ag-Bi-Co-Ni-As±U (five-element) veins are particularly prevalent across Central Europe, where this type of mineralization has been mined throughout the ages for its high-grade resources of Ag, Co, Ni, and U. The timing and the detailed geodynamic setting in which this style of mineralization formed remains, however, insufficiently understood due to the limited amount of geochronological data. In this contribution, we report the results of innovative LA-ICP-MS U-Pb geochronology on the carbonate gangue of Ag-Bi-Co-Ni-As±U mineralization from six districts in the Erzgebirge/ Krušné Hory metallogenic province of Germany and Czech Republic, with the goal to constrain the timing of ore formation in the context of Central Europe's geodynamic framework. In-situ U-Pb ages of twelve samples, including dolomite-ankerite, calcite, and siderite cogenetic with Co-Ni-Fe arsenides, range from 129.4 ± 8.2 to 85.93 ± 3.4 Ma. The ages of five-element and fluorite-barite-Pb-Zn veins from the same occurrence (Annaberg-Buchholz district) overlap each other, suggesting that these two styles of mineralization are genetically related and may form coevally. The compilation of geochronological data from other five-element occurrences in Europe suggests that the origin of this style of mineralization in Central Europe can be related to continental rifting associated with the Mesozoic opening of the Atlantic and/or the Alpine Tethys (200-100 Ma). This provides for the first time evidence for the formation of five-element vein mineralization across Central Europe in response to continental rifting.

Microplate interactions and hydrothermal activity at the Mangatolu Triple Junction, Northern Lau Basin

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The Mangatolu Triple Junction (MTJ), located in the northeast Lau Basin in the southwest Pacific, consists of three spreading centers that intersected in a ridge-ridge-ridge (RRR)-type configuration in the last 500,000 years. The northern part of the Lau Basin is dominated by a complex microplate mosaic, with three of the plates meeting at the MTJ. At least three distinct active hydrothermal systems are identified by plumes detected in the water column, at the center of the triple junction, at a large central volcanic complex coincident with the axis of the northeastern arm, and on an off-axis volcanic complex of the southern arm. A compilation of marine geophysical data (hydroacoustics, magnetics, and gravity) was used to construct the first comprehensive geological map of the MTJ at a scale of 1:200,000 to investigate the relationship between the mapped structure and magmatism and the known hydrothermal vents. Analysis of the geological map shows three stages of back-arc crust development, with the most crustal growth since the initiation of the MTJ in the northeastern arm, followed by the southern and western arm, which are in transition between rifting and magmatic spreading. The three hydrothermal systems are closely spatially associated with volcanic ridges (approx. 1100 m x 300 m x 30 m), most likely underlain by dike-like intrusions at the spreading center. Additionally, the vent sites inside the neovolcanic zone are proximal to large shield-like volcanic complexes (approx. 22.5 km x 6.5 km x 200 m high) and vent sites outside the neovolcanic zone are related to off-axis fissure volcanoes of the southern arm (approx. 17.5 km x 4 km x 650 m high). Furthermore, the hydrothermal vents are located in areas where high fault density, coincident with enhanced magmatic activity at the volcanic centers transitions into lower fault density. The distribution of hydrothermal venting shows the importance of large-scale permeability, in combination with structurally localized magmatism, which can be directly linked to the evolving microplate mosaic in the NE Lau Basin. The results of this study contribute to our growing understanding of the role of triple junctions in microplate formation and the initiation of hydrothermal systems in back-arc basins.

A simple and efficient method for Re-Os isotope analysis of sulfides using MC-ICP-MS

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The Re-Os isotope system is an effective tool in geological studies, especially in radiometric dating. As both Re and Os are highly siderophile and chalcophile elements concentrated in various sulfide minerals, the Re-Os geochronology has been employed for direct age determination of sulfide mineralization. However, the conventional analytical methods for the Re-Os dating are very complex and sometimes use reagents harmful to the human body. In this study, we propose an improved analytical method for Re-Os in sulfides by combining acid digestion using $HClO_4$ and sparging introduction of Os to MC-ICP-MS. In this method, 0.4 g of powdered sulfide was digested by 1 mL of $HClO_4$ in addition to 4 mL of inverse aqua regia in Carius tube. We applied this method to the separated chalcopyrite sample from Kamaishi Cu-Fe skarn deposit in northeastern Japan. The analytical results, including Re-Os concentrations, $^{187}Os/^{188}Os$, and $^{187}Re/^{188}Os$, are consistent with those by the conventional method digesting 0.5 g of the same sample by 10 mL of inverse aqua regia and measuring with N-TIMS. The lower total volume of acids for sample digestion in our method enables MC-ICP-MS analysis of sulfides with relatively lower Re and Os concentrations. Furthermore, the lower volume of sample solution is favorable for a simplified Os isotope analysis by the sparging method using MC-ICP-MS. Therefore, the new method may prove to be a simple and efficient analytical procedure for the Re-Os dating of sulfide deposits.

Mineralogical and geochemical in-situ analysis of fracture coatings in drill cores: A tool for the exploration of undercover ore deposits

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Fractures provide open permeable pathways for fluids to migrate along and can facilitate element dispersion from ore deposits into the surrounding rocks and overburden. Classifying the mineralogical and chemical composition of fracture coatings above ore deposits and understanding element migration along these pathways could be a useful proxy for mineral exploration. The development and creation of an in-situ method analysis for fracture coating is important to allow the study of fracture coatings to be applied to a wide range of geological environments and deposit types, especially where fracture coatings are not abundant. In the present study, we used fracture coatings in drill cores in proximity to the McArthur River unconformity uranium deposit, Athabasca Basin, Canada for the establishment of an in-situ method for analysing fracture coatings. High resolution compositional maps of mounted fracture coatings from backscattered electron (BSE) imaging show varying topography and mineralogy on fracture coatings including Mn and Fe oxides, clays and detrital silicate minerals. Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) experiments reveal optimum parameters for in-situ fracture coating analysis to overcome topographical constraints and speed up sample acquisition time without losing resolution and analytical sensitivity. Preliminary mineralogical and geochemical data from Scanning Electron Microscopy (SEM), Micro X-ray diffraction (µXRD) and LA-ICP-MS will be presented to demonstrate the potential of in-situ analysis of fracture coatings as a new geochemical tool to the mining industry for future mineral exploration.

Variability and controls on magmatic productivity in microplate domains of the northern Lau Basin

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The Rochambeau Rifts (RR) are a group of 'en echelon' back-arc spreading segments located in the northwestern Lau Basin, exhibiting fast spreading rates of ~110 mm/yr. In addition to eruptions at the ridge axes, recent marine expeditions to the area suggest that significant intraplate volcanism is occurring, represented by a dense array of cones, calderas, and other prominent volcanic features along and adjacent to the rifts. We have mapped the seafloor volcanic features at 1:200,000 using high-resolution marine geophysical and acoustic data compiled from the recent surveys in the area to establish the controls on the enhanced magmatic productivity. The mapping reveals that the volumetrically dominant volcanic products are flows and breccias flanking individual volcanoes and is distinguished by high acoustic reflectivity, with most of the material from proximal volcanoes. The 'Lobster Volcano', representing a major volcanic center, consists of a shield-like edifice, with a central caldera 2-2.5 km in diameter and E-W height variation of 20-100 m respectively, as well as elongated constructional features that are oriented radially away from the volcanic center. These structures are marked by alignments of volcanic cones and mounds interconnected by elongated ridges or fissure systems. Volumes were calculated using automated Triangular Irregular Networks (TINs) as a means of estimating rates of crustal growth. Effusive eruptions from the upper 600 m of the Lobster Volcano producing upwards of 46 km^3 of material is reported, among various other products on the order of several thousand m^3 to several km^3. Many studies in well-endowed ancient greenstone belts show that there is a close relationship between magmatic productivity and mineral endowment. The study of the Rochambeau Rifts shows that magmatic productivity may be significantly enhanced by crustal-scale permeability created in large-scale stress regimes related to microplate rotation or spreading ridge adjustments.

Regional structural controls on hydrothermal fluid flow in the North Fiji Basin

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The North Fiji Basin is the largest area of active back-arc spreading in the southwest Pacific, continuously opening since the Miocene. Previous studies have suggested a complicated history of microplate interactions, rotation and reorganization with crustal-scale structures having a strong influence on magmatic hydrothermal activity. We have mapped the location and orientation of crustal structures throughout the basin at a scale of 1:500,000 by interrogating satellite-derived Vertical Gravity Gradient (VGG). We compare the crustal structures with those on the seafloor to identify potential crustal pathways for melts and fluids throughout the basin. The deepest-penetrating structures are identified in the VGG by the transition between the gravity high and the gravity low anomalies and generally correspond to the largest faults. These measure approximately 100 kms in length and occur throughout the basin. According to work in Iceland and New Zealand the longest faults are the deepest and allow us to deduce that the faults seen in the VGG data of the NFB are crustal structures that likely penetrate through the full crust. The majority of the major structures are formed during accretion at spreading centers. However, in several areas, cross-cutting structures can be observed that may enhance crustal permeability. These are possible locations of off-axis hydrothermal systems. Similar-sized structures are common in ancient greenstone belt terranes, but their history is generally poorly known. The structures in present-day microplate mosaics provide a useful framework for understanding the possible original configurations of ancient structures, how and where crustal-scale faults form, and how they may be subsequently deformed.

Multi-kinetic apatite fission track thermochronology: deciphering the thermal history of Phanerozoic strata within the Peel Plateau NWT, Canada

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Apatite fission track thermochronology (AFT), can resolve detailed thermal histories within a temperature range corresponding to oil and gas generation and derived thermal histories can help in evaluating the maturity of source rocks within petroleum systems. In the Peel Plateau of the Northwest Territories, Canada, the timing of hydrocarbon maturation events are poorly constrained, as a regional unconformity at the base of Cretaceous foreland basin strata indicates that underlying Devonian source rocks may have undergone a burial and unroofing event prior to the Cretaceous. Herein, we have resolved the thermal history of the Peel Plateau through multi-kinetic AFT thermochronology. Three samples from Upper Devonian, Lower Cretaceous and Upper Cretaceous strata have pooled AFT ages of 61.0 ± 5.1 Ma, 59.5 ± 5.2 and 101.6 ± 6.7 Ma, respectively, and corresponding U-Pb ages of 497.4 ± 17.5 Ma (MSWD: 7.4), 353.5 ± 13.5 Ma (MSWD: 3.1) and 261.2 ± 8.5 Ma (MSWD: 5.9). All AFT data fail the $\chi 2$ test, suggesting AFT ages do not comprise a single statistically significant population, whereas U-Pb ages reflect the pre-depositional history of the samples and are likely from various provenances. Apatite chemistry is known to control the temperature and rates at which fission tracks undergo thermal annealing. The r_{mro} parameter uses grain specific chemistry to predict apatite's kinetic behavior and is used to identify kinetic populations within samples. Grain chemistry was measured via electron microprobe analysis to derive r_{mro} values and each sample was separated into two kinetic populations that pass the $\chi 2$ test: a less retentive population with ages ranging from 49.3 ± 9.3 Ma to 36.4 ± 4.7 Ma, and a more retentive population with ages ranging from 157.7 ± 19 Ma to 103.3 ± 11.8 Ma, with rmr0 benchmarks ranging from 0.79 and 0.82. Thermal history models reveal Devonian strata reached maximum burial temperatures (~165°C-185°C) prior to late Paleozoic to Mesozoic unroofing and reheated to lower temperatures (~75°C-110°C) in the Late Cretaceous to Paleogene. Both Cretaceous samples record maximum burial temperatures (75°C-95°C) also during the Late Cretaceous to Paleogene. These new data indicate that Devonian source rocks matured prior to deposition of Cretaceous strata and that subsequent burial and heating during the Cretaceous to Paleogene was limited to the low-temperature threshold of the oil window. Thermal history models derived from multi-kinetic AFT data can unravel complex thermal histories of sedimentary basins. Applying these methods elsewhere can improve the characterization of petroleum systems.

Searching for the record of Hadean primitive crust in the northeastern Superior Province

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Although we have growing evidence for Hadean mafic and felsic crust on Earth, continents today are formed around Archean cratons which are primarily composed of Meso- to Neoarchean rocks. Understanding the formation and nature of Earth's first crust is therefore a complicated problem; after more than 4 billion years of geologic processes, much of the early crust has been reworked or recycled. The goal of this study is to highlight the involvement of Hadean crust in the formation of Archean crust and determine if the reworking of Hadean material played an important role in the stabilization of Archean cratons. The Northeastern Superior Province (NESP) of northern Canada is comprised of two distinct terranes: the Hudson Bay Terrane and the Arnaud River Terrane. Both of these terranes are dominated by Neoarchean Tonalite-Trondhjemite-Granodiorite (TTG) rocks and granites. Their Nd isotopic composition suggests they have distinct crustal histories. Granitoids from the Hudson Bay terrane are characterized by low initial 143Nd/144Nd ratios, hinting at their derivation from an older crustal source, while granitoids from the Arnaud River terrane have more juvenile isotopic compositions, suggesting a limited contribution of an older crustal source. The age of the crustal precursor is difficult to constrain and depends on the assumed composition of the source rocks. Moreover, the long-lived 147Sm-143Nd isotopic system can often be disturbed in ancient metamorphosed rocks. We are proposing to combine high precision 142Nd measurements along with U-Pb-Hf in zircon analyses to better constrain the nature and age of possible precursors for the NESP continental crust. In-situ U-Pb-Hf in zircon has been demonstrated as a powerful tool to study crustal evolution and combined with 142Nd will provide detailed insight into the crustal history of the NESP. Because of the short ~100 Ma half-life of 146Sm (parent isotope to 142Nd), deviations in 142Nd/144Nd ratio can only be produced by Sm-Nd fractionation prior to ~4 Ga, in the Hadean. This novel approach has been locally applied to ~2.7 Ga granitoids in the Hudson Bay Terrane, suggesting the reworking of a >4.2 Ga mafic crust. This PhD project will apply these geochemical tools (142Nd, 143Nd and U-Pb-Hf in zircon) regionally across the NESP to better constrain the possible involvement of Hadean crust in the formation and stabilization of the Archean Superior craton. Understanding the early history of the Superior Province has important implications towards understanding how Earth's first continents were assembled.

Magmatic vs hydrothermal processes in the generation of carbonatite-related niobium ores within the Catalão II carbonatite complex, Central Brazil

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Carbonatites are the main source of critical raw materials such as rare earth elements (REE) and niobium, which concentrate through a combination of magmatic and carbohydrothermal processes. Magmatic differentiation of carbonatite magmas in examples from central Brazil has been closely linked with the concentration of niobium and the formation of nelsonites (apatite-magnetite rocks). Some of the most significant products of these mineralizing processes are the formation of Nb and REE minerals as pyrochlore (Na, Ca)2Nb2O6(OH, F), and monazite, as well as apatite, anatase, and magnetite. Despite recent advances, our understanding of how some of the world's largest niobium deposits have formed remains limited, hindering discoveries. Systematic core logging in the Boa Vista Niobium Mine in central Brazil disclosed three main domains for the Catalão II complex: (1) a deep carbonatite chamber zone (> 500 m depth) composed of intercalated carbonatites and nelsonites layers (intruded in turn by picrite dikes of ~40 cm thick); (2) a dike swarm zone (between 100 to 500 m deep) where carbonatite, nelsonite and picrite dikes intrude Neoproterozoic basement and; (3) a pyrochlore-rich regolith cover (0 - 100 m depth). Preliminary results indicate that pyrochlore is abundant in nelsonites (up to 40% modal) whereas rarer in carbonatites in both deep carbonatite plug and the dike swarm domains. In nelsonites, pyrochlore is associated with magnetite, apatite, phlogopite, and carbonate ± ilmenite. Phaneritic, pegmatitic, and panidiomorphic textures in nelsonites and carbonatites are ubiquitous in both the shallow dike swarm zone and the deep plug domain. Additionally, thermal conduction modeling carried out for carbonatite dikes at an initial temperature of 900°C showed that cooling is instantaneous. Cooling would take up to 30 hours for a 20 cm thick dike and 15 days for a 1 m thick dike. These models indicate that the large amounts of pyrochlore within magnetite-apatite-phlogopite-carbonate dikes from Boa Vista have crystallized nearly instantaneously but generated coarse-grained rocks instead of the expected fine-grained, quenching-related textures. In this sense, Boa Vista nelsonites are more akin to pegmatites from granite systems, which have also been modeled as generated by fast cooling. Additionally, considering that pyrochlore is absent from metasomatized host rocks, our preliminary assessment indicates that magmatic processes control the formation of niobium ores in Catalão II.

Trace elements in apatite in layered intrusions: insights into magmatic processes and application to mineral exploration

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Apatite is a weathering-resistant mineral that can be found in most igneous, sedimentary, metamorphic and hydrothermal rocks. Numerous studies have shown that apatite chemistry can be used as a provenance indicator for several kinds of rocks and/or mineral deposits, as well as providing information on magmatic processes. In igneous rocks, the chemistry of apatite primarily depends on magma composition, but may be further modified by processes during and/or after their crystallization. Even if these processes are known, it has not yet been determined if their influence on apatite chemistry is significant, nor if they could hinder or help the use of apatite as an indicator mineral for exploration purposes. This study uses LA-ICP-MS analyses (LabMaTer, UQAC) to obtain the full suite of trace elements of apatite from Sept-Iles (Quebec) and Bushveld (South Africa) layered intrusions, as well as Sept-Iles granites (most differentiated part of the intrusion). Our results show that the chemistry of apatite from mafic layered intrusions reflects magmatic differentiation and gives insights into the nature of the intrusions' magma. We show that the content of several incompatible elements (i.e. bulk D; including rare earth elements) increases during differentiation in apatite. In particular, a clear trend can be observed from the layered intrusion to the evolved granite of Sept-Iles. Apatites crystallizing from trapped liquid (intercumulus) display a different signature than those formed as a cumulus phase. Also, elements such as U, Th or Pb in apatite can reflect crustal contamination of the host intrusions. Even if apatite is already widely used as a provenance and petrogenetic indicator, apatite from mafic layered intrusions have not been taken into account by previous studies. However, mafic layered intrusions contain significant phosphorus, iron, titanium and vanadium resources, and possibly rare earth elements (hosted in apatite). Improving our understanding of apatite chemistry from layered intrusions will enlargen their use as a provenance indicator.