

SEG 2022 Conference: Minerals For Our Future

VMS Targeting Challenges: Rethinking the World-class IPB Province

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The Iberian Pyrite Belt (IPB) is a world-class VMS metallogenic district. The energy transition and the demand for critical raw elements such as Cu-Zn have led to renewed exploration campaigns in the IPB. The historical track record shows that improvements and changes in conceptual models, along with advances in geophysical methods, 3D geological modelling and a detailed geochemistry approach were critical for recent discoveries such as La Magdalena (2013, Spain) and Sesmarias (Portugal, 2014). The Albernoa exploration license is a greenfield project on the IPB that is located near Aljustrel (Cu-Zn active mine in Portugal), which has been the focus of some studies by several companies during the last years. Within the Albernoa exploration license, new methodologies recently developed for IPB have been tested to drive the exploration campaign. The combination of high resolution geological, mineralogical, geochemical and geophysical data allowed the identification of some anomalies in depth that are currently being tested by drill-holes. Airborne ZTEM and ground-based fixed loop SQUID TEM data identified EM responses with similar amplitudes to known massive sulfide accumulations in active mines, and which were not yet tested by drilling. Compilation of new and historical geophysical data and reprocessing and modelling using state-of-the-art techniques, such as 3D inversion of electromagnetic data, will yield better and more focused geophysical targets than previously available. For the Albernoa area, specific Alteration (AI) and Mineralization Indexes were developed based on micro-analytical studies. Metapelites record values of $(\text{Cu}+\text{Zn}+\text{Pb})/\text{Sc}$ and $(\text{As}+\text{Sb})/\text{Sc} > 10$, which allow to separate barren from altered/mineralized sequences. The same is observed for metavolcanics where AI_{major} ($\text{Fe}_2\text{O}_3+\text{MgO}+\text{MnO}/\text{Fe}_2\text{O}_3+\text{MgO}+\text{MnO}+\text{K}_2\text{O}+\text{Na}_2\text{O}$) varies between 0.25 to 1 and AI_{trace} ($\text{Zn}+\text{Cu}+\text{As}+\text{Sn}/\text{Zn}+\text{Cu}+\text{As}+\text{Sn}+\text{Rb}+\text{Ba}$) > 0.4 , suggesting hydrothermal alteration and mineralization. VMS targeting is a challenge and for new discoveries it is crucial to gather and model from macro to nanoscale.

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Timing of Orogenic Gold-forming Events Related to the Tectonic Evolution of California

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Orogenic gold mineralization within the Sierra Nevada foothills (SNF) and Klamath Mountains (KM) provinces in central and northern California, occurred episodically during ~50 million years of the Late Jurassic through Early Cretaceous and is linked to major tectonic events. Provincial gold mineralization in the KM lasted from ~160–140 Ma, whereas gold mineralization in the SNF lasted from ~160–115 Ma.

Initial gold mineralization impacted the then-contiguous KM-SNF arc at ~160 Ma, coincident with major far-field plate reorganization in the Pacific basin and compressional conditions. The next period of orogenic gold formation occurred at 155–140 Ma, synchronous with sinistral transpression along crustal-scale faults. Beginning around 140 Ma, the KM area was offset westward from SNF and the active arc, leading to the cessation of magmatism and hydrothermal activity within the KM; however, both continued within the SNF.

Sinistral movement along major faults in the SNF persisted until ~125 Ma, when another far-field plate reorganization in the Pacific basin led to a reversal of strike-slip motion along these faults. Most gold deposits of the ~190 km-long Mother Lode belt in the SNF cluster between ~130–125 Ma and are interpreted to be related to this transition to dextral motion along the terrane-bounding faults. A few younger ages suggest another period of gold mineralization at ~115 Ma in the northernmost (Alleghany district) and southernmost (Bagby district) parts of the SNF gold province that correlates to changes in the direction of movement for the Pacific and Farallon plates.

Despite a general overlap in timing of regional post-accretion magmatism and orogenic gold mineralization, there is no genetic link between these two processes. Major age differences between magmatism and mineralization on the local scale are the norm. When magmatism and gold mineralization are temporally correlated, geochemistry of trace minerals indicate that they are not genetically related.

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Nature and Paragenesis of Copper Mineralization of the Viscaria Property, Kiruna District, Northern Sweden

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The Norrbotten Region in Northern Sweden is recognized by its mining history for Fe-, Cu- and Au-, hosted within Paleoproterozoic-age rocks. Located 5km from the giant Kiruna IOA deposits, the Viscaria deposit was mined for copper in the 1980s. Copper mineralization at Viscaria comprises mantos distributed along several volcano-sedimentary horizons, that host massive to semi-massive magnetite and carbonate with generally disseminated pyrite – pyrrhotite – chalcopyrite – sphalerite.

Evolution of the deposit starts with pervasive and extensive biotite alteration followed by development of magnetite, calcic amphibole, chlorite and talc alteration. Two generations of paragenetically early, disseminated pyrite are replaced by pyrrhotite. Copper sulphide mineralization consists of semi-massive, disseminated and veined chalcopyrite; chalcopyrite is locally replaced by high-Fe sphalerite. Latest alteration comprises carbonate pyrite veins with vuggy textures and pervasive carbonate development.

To help understand the distribution of trace elements within Viscaria, ore and ore-related minerals including amphiboles, have been analyzed for specific trace elements. Preliminary results show that the later generation of pyrite is enriched in Co; pyrrhotite is enriched in Co and Ni. Sphalerite shows slight enrichments in Cd and, locally, in Co. Characterization of trace elements in the ore and alteration minerals along with textural and paragenetic observations will help to understand the evolution of the Viscaria hydrothermal system and its significance for exploration within the Kiruna District.

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The Importance of Bi-Te Nanoparticles in the Remobilization of Polymetallic (Au-Ag-Te-Bi) Orogenic Gold Mineralization

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Recent petrographic and microthermometric observations in orogenic gold systems imply that low-melting-point chalcophile elements can co-exist in the form of liquid-polymetallic Au-Ag-Te-Bi-melt-droplets with hydrothermal fluids to temperatures down to 135°C. These melts can efficiently scavenge Au from Au-undersaturated fluids through adsorption-reduction mechanisms along the polymetallic droplet-surface-area and, on further cooling, form Au-Ag-Te-Bi-minerals, visible as solid inclusions in pyrite, observed in various orogenic gold districts. Orogenic gold deposits commonly experience multiple hydrothermal events, which have the potential to remobilize polymetallic inclusions. However, their remobilization potential, mode of transport and chemical evolution remain elusive. Orogenic gold mineralization in the Abitibi (Canada) is distributed along the E-W striking Larder-Lake-Cadillac-fault-zone and hosted in lower-order structures that cut volcanic rocks and intrusions of the greenstone belt. These lower-order structures comprise brittle-ductile reverse shear zones and sub-horizontal tension veins, composed of quartz-tourmaline-carbonate. The shear-zones record two hydrothermal events 1) at ~2643 Ma, introducing the majority of gold as native Au and Au-Ag-Te-Bi-inclusions within pyrite; 2) a younger event at ~2607 Ma replaces sulfides and precipitates carbonate-chalcopyrite-native Au and carbonate-Au-Ag-Te-Bi-phases in pyrite fractures.

Here, we investigate the mineral-scale gold distribution of the Goldex deposit (Abitibi) by examining the potential of Au-Ag-Te-Bi-remobilization from pyrite-hosted, µm- to nm-sized polymetallic inclusions into texturally late sulfide fractures. Preliminary transmission electron microscopy (TEM) and nano-scale energy dispersive spectroscopy of two foils, extracted from texturally late pyrite fractures, hosting calcite-Au-Ag-Te-Bi-assemblages, reveal that infill of amorphous carbon forms layers, <300 µm-thick, at the interface between Te-Bi-phases, adjacent Au, calcite and pyrite host. The amorphous carbon phase contains sub-angular to rounded inclusions of Te-Bi nanoparticles between 10 to 50 nm. This suggests that late, reduced hydrothermal fluids dissolved pyrite-hosted Au-Ag-Te-Bi-inclusions and were remobilized along pyrite fractures. Our data imply that naturally occurring Te-Bi nanoparticles play a crucial role during the hydrothermal remobilization of already-present Au-Ag-Te-Bi-inclusions.

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Element Fluxes During Alteration in High-sulfidation Epithermal Systems

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The processes involved in the alteration of rocks associated with high-sulfidation epithermal ore deposits, which host significant quantities of gold and silver, cause a large-scale and complex migration of chemical elements. Elements can either be added into the system by magmatic-hydrothermal fluids or mobilized from one alteration facies to another due to the hydrothermal dissolution of minerals in the precursor rock and subsequent re-precipitation as new minerals elsewhere.

In this study, we present an elemental mass transfer analysis of alteration associated with the Pueblo Viejo Au-Ag(-Cu) high-sulfidation deposit, Dominican Republic. The whole-rock chemistry of precursor and variably altered andesite was used to determine the behavior of 64 elements during quartz-alunite, quartz-pyrophyllite, and chlorite-carbonate-kaolinite facies alteration. For high-sulfidation systems, relatively few mass transfer analyses have previously been successfully undertaken due to the difficulty in accurately identifying elements that remain immobile during alteration. This is necessary to remove the effects of significant bulk mass change on whole-rock element concentrations. Elements typically considered to be immobile in other settings where hydrothermal alteration occurs are unsuitable in the high-sulfidation environment, due to the highly acidic fluids responsible for alteration. We show that LREEs are immobile during high-sulfidation-related alteration because of the low stability of LREE complexes in the fluids (lower ionic potential) relative to HREE complexes, and the resultant formation of alteration minerals, such as woodhouseite, which preferentially retain LREEs on a local scale.

The calculated changes in elements during alteration were integrated with changes in mineralogy and mineral chemistry, determined using electron microprobe and laser ablation ICP-MS, to identify the minerals in which elements are hosted in both precursor and altered andesite. Understanding chemical and mineralogical changes that occur during alteration and mineralization provides an insight into the nature of ore-forming fluids and the changes in their physicochemical properties during intense fluid-rock interaction.

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Age and Genesis of W–Mo–Cu Mineralization, Gold Hill, Utah

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Utah's Gold Hill mining district hosts a Jurassic felsic pluton emplaced into a Mississippian–Pennsylvanian carbonate-dominated sedimentary sequence that is spatially associated with numerous polymetallic (potentially skarn-type) mineral deposits. The timing of mineralization in this district has not previously been constrained, resulting in uncertainty on the relationship between mineralization and pluton emplacement. This study presents new geochronological data for understudied W–Mo–Cu mineralization associated with a Jurassic pluton and outlines key relationships between the geological setting, magma composition, and paleo-fluid evolution of these polymetallic systems.

Six molybdenite samples dated using the Re–Os technique yielded five ages between 156.8 ± 2.2 and 154.4 ± 2.2 Ma that are consistent with existing unpublished zircon U–Pb ages for the proximal pluton (156.1 ± 1.8 Ma). This suggests that the pluton was likely the controlling factor in the generation of the molybdenite and associated mineralization in this area, indicating these are most likely skarn systems. However, an older age of 165.6 ± 2.4 Ma for the sixth low-Re sample provides evidence of multiple pulses of molybdenite mineralization, potentially indicating an earlier non-skarn molybdenite phase of mineralization or that some skarns are associated with a hitherto unidentified earlier phase of intrusion. This study also presents in-depth petrographic analyses from several mines in the district which outline key paragenetic relationships (cross-cutting and overprinting) and mineral assemblages that constrain the timing of alteration and mineralization. These include (1) early actinolite, apatite, diopside, and scheelite(?) skarn alteration, (2) a main molybdenite, chalcopyrite, bornite, pyrite, magnetite, hematite, and calcite phase of mineralization, and (3) post-skarn supergene malachite, azurite, chrysocolla, chalcocite, calcite, and limonite alteration. Future SEM imaging and EPMA will provide further insights into the genesis of W–Mo–Cu mineralization in the Gold Hill district as well as future exploration targeting in similar terranes.

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Paragenetic Relationships at the Tuvatu Alkaline Epithermal Gold Deposit, Fiji

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The Tuvatu alkaline epithermal Au-Te deposit is located on the island of Viti Levu, Fiji. Mineralization occurs in high grade, narrow veins that are hosted by the 4.85 Ma Navilawa monzonite, which forms a subvolcanic intrusion to a partially eroded shoshonitic volcano. The main mineralized zone strikes almost 900 m, has a vertical extent of more than 500 m, and remains open at depth. The deposit is currently under development and contains an indicated resource of 1.0 Mt grading 8.48 g/t Au (274,600 oz Au) and an inferred resource of 1.3 Mt at 9.0 g/t Au (384,000 oz Au) at a cut-off grade of 3.0 g/t Au. Microanalytical work reveals a complex overlap of high- and low temperature processes. Pervasive high-temperature potassic alteration of the Navilawa monzonite is characterized by abundant hydrothermal K-feldspar and secondary biotite. The potassic-altered monzonite is crosscut by first-stage epithermal veins hosting abundant base-metal sulfides. These base-metal rich veins contain euhedral pyrite as well as dendritic aggregates of chalcopyrite, sphalerite, and galena. Mosaic quartz is the principal gangue mineral. Second-stage epithermal veins host the majority of the Au mineralization. Native gold and telluride dendrites occur with roscoelite in bands of mosaic quartz. Relic microtextures suggest that the quartz formed as the result of the recrystallization of non-crystalline, microspherical silica. The microspherical silica is interpreted to have formed under conditions of rapid silica supersaturation caused by the flashing of the hydrothermal fluids, which also triggered gold deposition at far-from equilibrium conditions. Formation of the high-grade vein material was followed by the deposition of chalcedony or euhedral quartz. The third and final stage of epithermal mineralization consists of barren carbonate veinlets. Identification of fluid flashing during deposit formation has important implications for further exploration at Tuvatu and advances the model for how alkaline epithermal deposits form.

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Unraveling Bulk-rock Compositional and Metamorphic Mineral Assemblage Zoning at the Laronde Penna Volcanogenic Massive Sulfide Deposit

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This study introduces a workflow that was developed to identify geochemical and mineralogical gradients in ore deposits by non-destructive drill core analysis. This was achieved by compositional analysis of drill core by continuous XRF core scanning using the device manufactured by Minalyze AB and conducting short- and long-wave hyperspectral imaging of the core using instrumentation at Terracore in Reno, Nevada. Both datasets were co-registered to allow cluster analysis. Based on the clustering, a subsampling strategy was developed to allow further petrographic investigations on representative thin sections and automated mineralogical analysis.

The workflow developed was tested on drill core from the LaRonde Penna deposit in the Archean Abitibi greenstone belt in Quebec. The deposit is a world-class gold-rich volcanogenic massive sulfide deposit which contains an endowment of 71 Mt of ore grading on average 3.9 g/t Au. The ore lenses and their host rocks have been affected by regional greenschist to lower amphibolite facies metamorphism.

The study of core from LaRonde Penna demonstrates that the metamorphoses hydrothermal alteration halo is strongly zoned. Whole-rock geochemical variations along core intersecting the alteration halo and ore zones closely correlate with metamorphic mineral assemblage zoning. The observed variations in the composition of the felsic volcanic rocks in the footwall of the massive sulfide lenses were introduced during hydrothermal alteration as the intensity of fluid-rock interaction was most pronounced in proximity to the ore zones and decreased outwards away from the major zones of hydrothermal upflow. The composition of the hydrothermally altered rocks controlled metamorphic mineral assemblage formation during subsequent metamorphism.

The research has implications to mineral exploration for VMS deposits in high-grade metamorphic terrains as it establishes the link between whole-rock geochemical gradients and metamorphic mineral assemblage variations at greenschist to amphibolite metamorphic grade

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Importance of Foundational Petrology and Geochemistry for Evaluating Igneous Sources to Base Metal Mineralization in SW Ireland

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County Limerick contains the largest exposure of Carboniferous igneous rocks in Ireland, which occur as diatremes, lava flows, dykes, hypabyssal intrusions, and tuffs that are collectively known as the Limerick Igneous Suite (LIS). The LIS is comprised of two smaller, separate igneous packages: 1) the Knockroe igneous units, which range from alkaline basalts to trachyandesites, and 2) the Knockseefin igneous units, which range from alkaline basalts to basanites. Both units have undergone significant amounts of chlorite-calcite \pm prehnite alteration, minor pyrite mineralization, and are spatially associated with multiple Zn-Pb sulfide prospects in SW Ireland.

Uranium–Pb dating of apatite establishes an igneous crystallisation age of c. 350 Ma for the Knockroe units. Bulk rock Sr and Nd isotopes from the least altered Knockroe samples range from 0.70301–0.70454 and 0.512457–0.512493, respectively. Strontium isotopes for the least altered Knockseefin samples range from 0.70325–0.70386 and the Nd values range from 0.512431–0.512437. Altered samples are buffered against changes in Nd, but some analyses show excursions towards radiogenic Sr, indicating contamination from Carboniferous seawater and/or introduction of Rb. The latter alteration returned ages within uncertainty of the U–Pb dates.

The world-class Lisheen and Silvermines deposits are ~50 km north of the LIS and have Re–Os ages of 346 ± 3 Ma and 334 ± 6 Ma, respectively, which correspond to the ages of the LIS. However, the Nd and Sr isotope signatures from the LIS are very different than those previously obtained from gangue carbonate and barite associated with hydrothermal Zn-Pb-Fe sulfides at the Navan Mine. Using the results from Navan as a proxy for Irish-type mineralization suggests the LIS is not necessarily a mineralization source. However, the U–Pb ages indicate the LIS may have been a heat source along the Iapetus Suture Zone, which could have helped to drive Irish-style mineralizing systems.

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The Source of Mineralization in Stratabound V Rich Deposits in the Yukon Territory, Canada: Evidence from V Isotopes

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Vanadium is becoming increasingly more important, both for its use in steel needed to build new infrastructure but also for its use in long-life batteries. As such, new sources of V need to be discovered and exploited. A potential source is highly metalliferous shales. One of the highest grade locations is in northwest Canada, where it has been found at concentrations of approximately 0.5% over tens of metres. However, it is not clear how these form so it is difficult to develop strategies for finding larger or higher grade deposits. One of the more popular mechanisms proposed is direct precipitation from seawater, however it is not clear how such high concentrations of V could be maintained for so long if reductive trapping of V from seawater were the only source. Hydrothermal fluids are another potential source but to date no known vent site has been found near these systems.

V isotopes, measured as $\delta^{51}\text{V}$, offer a chance to better elucidate the source of V as V deposited in different depositional settings and hydrothermal V all have different $\delta^{51}\text{V}$ signatures. In the modern environment $\delta^{51}\text{V}$ is $-0.15 \pm 0.15\text{‰}$ for hydrothermal sediments, $-0.9 \pm 0.1\text{‰}$ for oxic sediments, $-0.5 \pm 0.1\text{‰}$ for anoxic sediments and $-0.2 \pm 0.1\text{‰}$ for euxinic sediments. Our results range from 0.11 to -0.33‰ $\delta^{51}\text{V}$. While a few samples are slightly heavier than the range expected for a hydrothermal source there is no alternative probable source with a positive $\delta^{51}\text{V}$ so this is probably evidence of a minor amount of closed system behaviour. Further, while some of our results could be explained by euxinic deposition this is unlikely as there are large concentrations of barite found with the V rich horizons, something unlikely to occur in euxinic settings where all sulfate has been reduced to sulfide.

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Relationship of Magmatic and Ore-forming Processes in Andesitic Volcanoes – Example from the Štiavnica Stratovolcano, Slovakia

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In big, long-living volcanic centres, such as Štiavnica andesitic stratovolcano in the Western Carpathians, there are present diverse styles of ore deposits with a variable metal endowment. Based on LA-ICP-MS, EMPA and microthermometry data from rocks, melt inclusions and fluid inclusions, magmas and most deposits were sourced from an upper crustal (~1 to ~3 kbar) reservoir that was active more than 3 My. Ore deposits were formed during periods of reservoir cooling when the residual melt reached fluid saturation. This melt is represented by evolved rhyolitic melt inclusions of a roughly stable composition, hosted by rock-forming minerals from different stages of magmatic activity. Fluid inclusions in most deposits (except of brines in Cu-Au skarn-porphyries) showed increased B, As, Sb concentrations indicating that the main source of fluids was a magmatic supercritical fluid contracted to liquid during ascent from the reservoir or a contracted vapor resulting from fluid heterogenization. The relatively constant composition of most studied elements, high Cs contents, and agreement with the published fluid-melt fractionation factors indicate a common long-lasting source of magmatic fluids, exsolved from the evolved interstitial melt. The fluids were continuously exsolved and accumulated but liberated during periodical tectonic events. They include migration via contraction fractures (Pb-Zn-Cu stockwork in granodiorite), ring fractures and shear zone induced by a sector collapse of the volcano (early Au-Ag-Pb-Zn-Cu veins), along with porphyry stocks and ring dikes as a precursor of a caldera collapse (Cu-Au skarn-porphyries), and faults of a resurgent horst uplift (late Ag-Au-Pb-Zn-Cu veins). Ore precipitation was triggered by mixing of magmatic and meteoric water (stockwork), boiling of decompressed fluids (early veins), cooling of contracted vapor affected by late fluid heterogenisation (skarn-porphyries) and mixing+boiling (late veins). Our results show that external factors, rather than melt and fluid compositions, primarily control the different metal endowment of the deposits.