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Inaugural Lecture

The Next Generation of Applied Geochemists: The Legacy and Geochemical Advances of Dr. Peter Alan Winterburn (1962 – 2019)

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Dr. Peter Winterburn worked in industry as a geochemist for 20 years in more than sixty countries through positions with Anglo American and Vale. In 2013, he began a five-year term as the NSERC/Acme

Labs/Bureau Veritas Minerals Executive Industrial Research Chair at the Mineral Deposits Research Unit (MDRU) at the University of British Columbia.

Peter's tragic death in June of 2019 was a profound loss not only to the geochemical community, but to the wider mining and scientific community. Peter's position at MDRU demonstrated his rare ability to link industry and academia to tackle complex scientific questions. His approach spanned across several scientific disciplines to solve industry challenges by optimizing existing tools and developing new methods.

During his time at MDRU, he supervised 13 students at undergraduate, master's, and postdoctoral levels in exploration geochemistry projects. This research focused on developing effective strategies for detecting mineral deposits in covered terrains, which continues to be one of the major challenges for the mineral exploration industry today. Peter had a genuine curiosity in understanding the interaction between sub-surface geology and the surficial environment and instilled this sentiment in his students. The research projects completed under his supervision challenged and improved conventional anomaly formation models, emphasized the fundamental importance of regolith/terrain mapping, and dove into lesser studied components such as hydrocarbons and microbial interactions in the mobilization of metals at depth. Most notably, the research he led highlighted the importance of structural weaknesses in cover for the formation of anomalies at surface, demonstrated the importance of understanding the climate and materials sampled, and identified bacterial DNA as an exciting new tool for identifying concealed mineralization. To meet the challenge of mineral exploration of the future, we must continue to lead with curiosity – and to provide opportunities for innovation and collaboration to the next generation of geochemists.

Peter's legacy will always be more than the geochemical advances he made during his esteemed career. Peter invested his time into the teaching and mentorship of students and to the development of the future generation of applied geochemists. Peter continues to teach us today, by showing us that the most enduring legacy in science is to teach your students how to think – not what to think.

Keynote Lectures

Data Digs Deeper: using data science to transform geochemical understanding into discovery

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In the modern era of mineral exploration and mining, geologists are routinely using geochemical data through all parts of the mining value chain – from greenfields exploration to deposit modelling, to geometallurgical domaining, to optimization of the mill & flow sheet, and finally restoration. Geochemical data is a key quantitative touchstone that can be used and re-used across the life cycle of a project. However, in this modern exploration environment we are faced with new challenges with the necessity of exploring under cover for blind deposits.

As the speed and volume of data collection rapidly increase in mineral exploration campaigns, mines, and near-mine environments, data processing methods must become more sophisticated to efficiently deal with this data deluge. Machine learning workflows and machine-assisted modelling will become routine parts of the mining value chain; integrating traditional geoscience knowledge with data science expertise will be critical to successful algorithm deployment.

This session is entitled "squeezing more from our data", but as geochemists we are routinely pushing our data further than ever before. In addition to this, we have the blessing (or curse!) of more voluminous data rooms, with more data streams being collected every year on every project. One of the questions we must address as an industry is not "how much more data should I collect?", but rather "which data types will be most significant and impactful on this specific project?"

To extract meaningful value from our data, to get the most pertinent and relevant information to help us understand and explore for our deposits, we must ask the right questions. This is where geoscientists and data scientists must work closely together because the data scientist can easily script the code to manipulate the data, but the right question must come from the geoscientist.

The first part of this keynote will cover three separate examples of common geochemical problems, and what types of solutions adopted from the data science field to solve them:

1. Data Deluge
2. Data Heterogeneity
3. Geochemistry in the Data Stack

In addition, five fields that are common to both geochemistry and data science will be compared and contrasted:

1. Transformations
2. Class Imbalances
3. Correlated Factors and dimensionality reduction
4. Scaling
5. Clustering, with particular attention to selection of appropriate algorithms

The latter part of this keynote will be devoted to a case study of a low sulphidation epithermal Au system, where a traditional geochemical interpretation workflow (lithogeochemical classification, identification of alteration assemblages, and exploration vectoring) is embedded with machine learning algorithms to make the workflow more robust, flexible, and reproducible.

The low sulphidation epithermal deposit case study will use many exploratory data analysis geochemical techniques that are routine and familiar to both the geochemist and the data scientist, such as clustering and classification, as well as incorporation of data science techniques, like decision trees and random forests, to allow the geochemist to quantitatively interrogate results and define thresholds.

The result is a robust, re-usable lithological and alteration classification scheme that can assist in vectoring and identification of a near-hit, as well as a set of exploration implications (identification of specific rock types and alteration styles associated with the highest grades).

In collaborative team environments, geochemists and data scientists can work together to turn data into information by asking the right questions and critically evaluating the answers, therefore enabling us to realize the discovery potential in our data.

Fundamental Laws of Geochemical Elements and Anomaly Recognition for Mineral Exploration

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Establishing the basic laws of geochemical elements is a century-long task of geochemistry. While the laws of the atomic properties of elements have been shown to be fundamental and universal in determining how elements behave in geochemical and geophysical processes, knowledge about the distribution of elements in earth materials often lacks a physical basis. In geochemical exploration, the concepts of background and anomaly are used to distinguish between normal abundances of elements in barren earth material and local additions due to mineralization. Separating anomalous geochemical patterns from the background geochemical landscape has become a primary task for geochemical applications in exploration. However, due to the limitations of data representing anomalies compared to the background, most methods developed for the above purpose can only describe the background using an appropriate model and set thresholds to screen out anomalies (outliers). In these types of treatments, quantitative models are used to describe the context rather than the abnormality. Simply put, values that are unlikely to belong to the background distribution are separated as anomalies. What do we know about anomalies in this context? How to describe the anomaly? How to distinguish anomalies from backgrounds? What are the distribution laws of elements in an anomaly and how they differ from the distribution laws of elements in background landscape? This is not only a fundamental problem in geochemical exploration, but also a common problem in the study of extreme geological events that occur in a relatively narrow space-time interval, but are abnormal in material accumulation, element enrichment, or energy release. The current report updates on progress of development and applications of the Local Singularity Analysis (LSA) theory and methods for quantitative description, modeling and recognition of anomalies caused by mineralization. These include a new physical concept of fractal density to characterize the physical property of geochemical anomaly, a local singularity analysis model to describe the scaling laws of element concentration distribution in anomalies, and a suite of methods for identification of anomalies from background for supporting mineral exploration.

Sourcing of critical elements and industrial minerals from mine waste/ore deposits – The role of Geochemistry

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In metal mining, in most cases only a minor percentage of the extracted materials are the valuable target elements (e.g., Fe or Al ores 20–70%, Zn 2–15%, Pb 1–10%, Cu 0.2–6%, REE 0.1–0.5%, Au 0.5–20 g/t). Thus, the vast majority of the extracted material is defined as waste, which is deposited in disposal facilities like tailings impoundments, lakes, or the sea and in waste-rock dumps or is backfilled into open pits or underground mines.

These mine wastes are the source of environmental pollution, for example via Acid Mine Drainage formation, and fatal risks like during dam failures. To minimize the risk from mine waste in the future, mine waste has to be eliminated. This applies for both, fresh mine waste and historical mine waste. Latter can still contain important metal contents (specifically the overlooked critical metals like REE, PGE, and battery metals like Co, Ni, Li, Mn), and have therefore a high potential for successful exploration. Additionally, other georesources as sand and industrial minerals will increase the demand in the future and metal mining can provide an important portion as secondary by-products. An inline separation sequence can separate the material in different mineral groups producing economic valuable mineral concentrates. The major volumes of silicates are non-hazardous and, if separated accurately, they can be used as industrial minerals or for construction material. Key is that reactive minerals like pyrite are separated from the non-reactive mineral assemblage. Also, high-tech applications can be found for these materials as for example quartz for solar cell production and glass industry or micas and pyrite for semi-conductors for solar cells. Pyrite itself is the source of acid mine drainage (AMD), but it is also a resource for Fe, S, H_2SO_4, and valuable trace elements like Ni, Co, Cu, Zn, Au, Ag, Bi. Sulfuric acid, key reagent for fertilizer production will need new sources, as due to decarbonization of the modern society, the main todays source of sulfuric acid production, the desulfurization of fossil fuels, will break away. Thus, pyrite looks into a bright future, giving the possibility to solve the problem of acid mine drainage due to remining and desulfurization of mine wastes.

Oral Presentations

Technical Session 1

Exploration geochemistry: Present and future challenges

The challenges of geochemical exploration in the subarctic terrain of the Scandinavian Peninsula

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Northern Scandinavia has a long mining history. Traditionally, exploration relied on boulder-hunting and geophysics and numerous orebodies have been discovered by applying these methods. However, the low-hanging fruit has been picked and exploration methods need to become more and more sophisticated in order to detect mineralizations that until now have remained hidden.

Geochemistry is one of the keys, including soil geochemistry and biogeochemistry. Both soil and vegetation contain plenty of information about the bedrock underneath.

Soil geochemistry*:* Given that most of the soil cover in Scandinavia is of glaciogenic origin, understanding the genesis and the three-dimensional architecture of the overburden is crucial for interpretation of any soil geochemical data set. The glacial stratigraphy in Northern Sweden tends to be complex with several till units which are deposited during different glacial events and from different directions. Thus, any geochemical anomaly in the glacial sediments needs to be assessed in regard to which till unit it belongs to, from which direction and how far it has been transported. Satellite and even more important, LiDAR images are an invaluable asset when it comes to interpreting glacial sediment types, landforms and palaeo-iceflow patterns. In addition, till lithological analyses and clast fabric analyses can be carried out.

Biogeochemistry: Boliden Mineral has tested biogeochemistry for exploration purposes. Samples have been taken from trees, mainly Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). The preliminary results are encouraging.

This presentation will provide insight into the challenges Boliden Mineral's exploration faces in the subarctic terrain of northern Scandinavia and hopefully aid in choosing the right method for the right environment and the right purpose.

Detrital zircon chemistry, a tool for exploring copper porphyries: the Cerro Colorado district case study

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High magmatic fertility for porphyry copper deposits results from long-lived and deep-seated magma, evolving during intense compressional tectonic phases and reaching high hydration and oxidation states. These tectono-magmatic settings provide favorable physico-chemical conditions during magma fractionation preceding the ore formation processes.

The primary control on magma fertility is high water content (Richards, 2011). This fertile magmatic condition can be identified in zircon trace element chemistry using recognized geochemical proxies such as the Eu/Eu* and 10^4(Eu/Eu*)/Yb ratios, which are considered among the best zircon magmatic hydration indicators (Lu et. al 2016). Furthermore, zircons can preserve the chemical parental magma signature while submitted to drastic external changes (alteration, metamorphism, etc.) and long-distance detrital transport.

In many prospective areas of Northern Chile, intrusions derived from highly fertile magmatic stocks are unconformably overlain by younger sedimentary sequences. Analyzing the age and chemical composition of transported zircons hosted in these sedimentary units can support the discrimination of fertile arc segments from un-prospective terranes, over large detrital source areas.

This case study is based on LA-ICP-MS analyses performed on zircons derived from post-Oligocene sedimentary sequences present in the Paleocene-Eocene Cerro Colorado district of Northern Chile. In this study, U-Pb dating on detrital zircons yielded ages ranging from Carboniferous to Pliocene, in concordance with the recognized district geology. Subsequent fertility assessment, combining the U-Pb age with the corresponding trace element mineral chemistry for each grain, identified four magmatic hydration peaks during the Upper Cretaceous, Paleocene-Eocene, Upper Eocene, and Middle Miocene. These magmatic hydration peaks are coeval to well documented compressive tectonic phases in Northern Chile. Finally, the highest magmatic hydration values obtained in this study are associated to ages ranging between 54 and 51 Ma, coincidental with the known age of emplacement of the intrusive phases associated with the mineralization of the Cerro Colorado mine.

This study confirms the effectiveness of detrital zircon chemistry as a powerful regional exploration tool for porphyry copper deposits in Northern Chile, with the potential to identify fertile arc segments and track compressive tectonic phases.

Extending the size of the alteration footprint around the Hemlo Au deposit, N. Ontario: application of epidote and chlorite mineral chemistry in Archean greenstone terranes

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The Hemlo deposit is a world class Archean Au deposit situated in Northern Ontario, Canada with historic production of >21 Moz of Au over 32 years of continuous operation. The deposit has a strike length of ~3 km with a well-documented alteration footprint surrounding mineralization. LA-ICP-MS analyses of epidote, chlorite, and pyrite from within and surrounding the deposit have identified major and trace element variations in mineral chemistry that allow for the discrimination of deposit-proximal and deposit-distal signatures.

Epidote compositions vary with distance from Hemlo, with the highest concentrations of As and Sb in epidote proximal to the mineralized zones. Anomalous trace element compositions in epidote can be detected up to 1.5 km further than the mapped alteration footprint. Chlorite also displayed variation in trace elements with deposit-proximal chlorite displaying exponentially higher Ti/Sr and V/Co values than deposit-distal and intrusion-related chlorite. The Ti/Sr ratio for chlorite expanded the geochemical footprint of the Hemlo deposit by up to 1 km. Pyrite displayed anomalous enrichments in a number of elements, with Au, Te and As proving to be the most effective pathfinder elements in pyrite as they were detected at anomalous concentrations up to 2.5 km from the deposit.

Several post-mineralization intrusions that surround the deposit were evaluated using epidote and chlorite chemistry to assess whether they generated any false positive geochemical anomalies. The distal post-mineralization intrusions have epidote with consistently low As and Sb concentrations and elevated Fe/Al values relative to deposit-related epidote and can be easily distinguished. Intrusion-related chlorite displayed low Ti/Sr and V/Co values relative to the deposit chlorite and was also found to be more enriched in Fe relative to deposit-proximal chlorite. These results indicate that the post-mineralization intrusions did not produce false positive mineral chemistry anomalies.

The systematic variations in syn-mineralisation epidote and chlorite compositions around Hemlo suggests that methods developed for investigating geochemical footprints defined by green rock alteration around porphyry systems may also be applicable to Archean orogenic gold deposits.

Microbial biosensors of buried mineralization

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Mineral exploration is becoming more challenging as undiscovered deposits are likely buried beneath appreciable overburden. The development of innovative exploration strategies and robust techniques to see through cover is imperative to future mineral deposit discovery success.

Microbial communities are sensitive to subtle environmental gradients, and they will reflect these gradients through spatial variability. Variations in microbial community profiles, induced by chemical and physical differences related to geology, are detectable and can be used to vector toward discrete geological features. Results to date demonstrate viability of microbial fingerprinting to directly identify the sub-crop of mineralization at two porphyry copper deposits in British Columbia and two kimberlites in the Northwest Territories. Microbial community profiling of soils above these deposits reveals significant microbial community shifts with a distinct species-level community response, correlated with subsurface ore mineralization.

Outcomes from these deposit-scale studies have highlighted the potential for geomicrobiological tools and techniques for successful application to through-cover mineral exploration. Current research focuses specifically on reducing fundamental unknowns about the behaviour and variation of microbial communities in response to chemical and physical changes in the environment. This includes assessing how microorganisms sense and utilize economic minerals; exploring microbial-community composition and metabolic potential in northern soils in response to changes in temperature; and assessing the impact of transport and storage on the persistence of microbial-community anomalies in soils. These investigations serve to support the use of microbiological-based mineral exploration in different mineral systems, in various terrains and climates, and to develop practical and informed transport and storage protocols for industry.

Magmatic sulfide-bubble compound drops are crucial for the formation of Cu-rich massive sulfide ores in oceanic settings

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The reason why some hydrothermal sulfide ores in oceanic settings are enriched in Cu while others are barren is still controversial, in part due to disagreements regarding which geological processes allow Cu transfer from magmas to ores. Two phases for which Cu has a strong affinity may be extracted from magmas during their evolution: a volatile-rich fluid phase and a sulfide phase. Extraction of magmatic sulfides have often been considered detrimental for transferring Cu towards the surface because sulfides are denser than the magma and may sink towards the bottom of the magmatic chamber. Recent experimental studies suggest however that sulfides may be attached to low density bubbles and may float at the roof of the magmatic chamber where they can be mobilized during eruptions. Identification of the sulfide-bubble association in natural magmas remains scarce. We present a unique example of well-preserved sulfide-bubble associations in the slab-decoupled submarine melts of Fatu Kapa (NW Lau back-arc basin, SW Pacific) associated with Cu-rich massive sulfide deposits. Based on textural evidence, we identify two potential ore-forming processes: (1) formation of copper-hydrosulfide complexes in the fluid phase prompted by copper and sulfur transfer from the sulfide to the associated bubble during ascent and (2) interactions between the hydrothermal fluid and the sulfide blebs preserved during ascent. We infer that the second process may explain the Cu-rich composition of Fatu Kapa massive sulfide ores because hydrothermal fluids display no evidence of mixing with an exsolved magmatic fluid. This result has implications for the genesis of Cu-rich hydrothermal sulfide ores associated with oceanic slab-coupled magmas in the upper crust, where the first process may dominate according to the volatile-rich composition of these melts and to the common occurrence of mixing between hydrothermal fluids and exsolved magmatic fluids in these settings. The high efficiency of this process that leads to the total consumption of sulfides would explain why sulfide blebs associated with bubbles are rarely observed in these settings.

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Base metals and PGE behavior in slab-decoupled oceanic felsic melts: insights from the Fatu Kapa area (NW Lau back-arc basin, SW Pacific)

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While the behavior of chalcophile elements in oxidized slab-coupled melts in the upper-crust or in reduced mafic mid-ocean ridge basalts (MORB) is becoming well constrained, our understanding of their behavior in slab-decoupled felsic melts remains scarce. We present base metals and PGE concentrations measured on submarine and slab-decoupled magmatic rocks of Fatu Kapa (NW Lau back-arc basin) that form a well-defined transitional suite from basalts to andesitic and dacitic lavas. These lavas evolve either mainly through fractional crystallization from basalts to andesitic lavas (group 1A) or through fractional crystallization from basalts to dacites coupled with assimilation of felsic melts generated by partial melting of hydrothermally altered oceanic crust (group 1B). Regarding chalcophile elements behavior, melts from group 1A may be split in three stages of evolution. In the first stage, increases in of highly chalcophile elements (e.g., Cu, Au, Pd, Pt, Rh) with decreasing MgO attests that these magmas are sulfide undersaturated, which is likely due to depths of partial melting deeper than those where MORB are generated. At ~7 wt.% MgO sulfide saturation occurs as attested by a drop in Cu, Au and PGE concentrations. Modelling of base metals behavior shows that ~0.175 wt.% of sulfides are exsolved during this second stage, while at the onset of magnetite crystallization (~4 wt.% MgO) ~0.35 wt.% are extracted. Modelling of Cu behavior in group 1B reveals that higher volumes of sulfide melts are extracted from these melts, ranging from 0.45 wt.% to 0.75 wt.%. Moreover, modelling of base metals suggests an exogenic input of As, Sb and In in these melts which can be attributed to assimilation of ores through partial melting of the hydrothermally altered oceanic crust. As Fatu Kapa melts are associated with Cu and Au-rich massive sulfide deposits, these results suggest that oceanic felsic rocks may be an important target for ore deposits exploration.

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Newmont Geochemistry, the Untold Story

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As Newmont moves into its 101st year, there is an opportunity to reflect on a history of commitment to exploration, innovation, and technology. Newmont's 100-year journey has populated the gold explorers' toolbox with geophysical techniques as notable as induced polarisation; however, the parallel story of the development of industry-leading geochemistry is yet untold. Although there are no silver bullets in gold exploration, a 40-year effort by Newmont's geochemistry team with a focus on sampling theory, data integration, and aggressive field programs has resulted in proprietary geochemical exploration tools which are still seeing active development and deployment.

Newmont's Bulk Leach Extractable Gold (BLEG) stream sediment sampling technique was developed over the 1980s and 1990s as an efficient and reliable low-level regional reconnaissance screening tool. As gold is a notoriously difficult element to analyze in stream sediments due to highly variable field duplicates, the technique was engineered to achieve acceptable reproducibility of results at the lowest detection limits available at the time. Amongst several discoveries, Newmont BLEG is credited

for revealing the world class Batu Hijau Cu-Au porphyry system in Indonesia (Maula and Levet, 1996).

More recently, exploration has trended away from a focus on outcropping systems into the cryptic world of undercover targeting. This focus has seen Newmont's next generation of geochemical tools emerge; Deep Sensing Geochemistry (DSG) and Terrain Mapping Geochemistry (TMG). Although DSG was first named publicly in 2013, these techniques were developed following years of internal and external research in fine fraction geochemistry, applied field geochemical and regolith control, and advances in analytical laboratory capabilities using ultrapure digestions and instrumentation pushing elemental detection limits below crustal abundance.

Explorers today are experiencing a geochemical renaissance where these tools, leveraging applied geochemistry fundamentals are integrated with other advanced exploration tools and datasets to deliver the next generation of discoveries.

Stream sediment geochemical and indicator mineral signatures of the Casino porphyry Cu-Au-Mo deposit, Yukon, Canada

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A detailed indicator mineral and stream sediment geochemical study was conducted around the Casino calc-alkaline porphyry Cu-Au-Mo deposit in the unglaciated terrain of west-central Yukon, in northwestern Canada. The deposit is one of the largest and highest-grade undeveloped porphyry Cu-Au-Mo deposits in Canada and is hosted in Late Cretaceous quartz monzonite and associated breccias. At 22 sites on local creeks, a large (10-14 kg) coarse-grained stream sediment and a smaller (1 kg) fine-grained stream sediment sample was collected. The Casino deposit has an obvious indicator mineral signature in the <2 mm heavy (>3.2 specific gravity (SG) and mid-density (2.8–3.2 SG) fractions of stream sediments that is detectable at least 14 km downstream and includes gold, chalcopyrite, tourmaline, molybdenite, sphalerite, jarosite, goethite and pyrite. The crystal form and trace element chemistry of tourmaline from stream sediments is particularly diagnostic of the presence of the porphyry deposit. The geochemical signature of the deposit is best defined by Ag, As, Au, Cu, Mo, Pb, and Zn in the <0.177 mm fraction of stream sediment. Similar indicator mineral and sediment geochemistry patterns occur in creeks downstream of other local porphyry occurrences. Our results indicate that the addition of indicator mineral sampling to routine stream sediment sampling protocols in this unglaciated region of the Yukon will be beneficial to porphyry Cu exploration programs.

Impacts of environmental variables on biogeochemical results - orientation survey in the Peräpohja Belt, northern Finland

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The potential of biogeochemistry, i.e., plant ionome, for mineral exploration has been previously demonstrated in case studies in Fennoscandia, where soils are formed on glacially transported sediments. Because plant element uptake is controlled by a variety of processes, anomalies can be weak and not necessarily caused by the underlying bedrock geochemistry. The goals of this study were: 1) to understand the effect of selected environmental variables on plant ionome and 2) to propose a compositional data analysis approach for selecting the most effective element log-ratios, plant species and their tissue types, and elements for a routine exploration survey in an orientation survey set-up.

The test site is located on Au-Co prospects at Rajapalot, northern Finland, stretching over highly variable metasedimentary bedrock in an undisturbed boreal forest. Sampling microsites included well-drained soils and edges of the peatlands over a variety of overburden thicknesses, which resulted in a broad spectrum of rootzone conditions. Based on existing geophysical data sets (magnetic, resistivity), used as proxies for lithological contrast, and nature type mapping, we set up a stratified random sampling design (n=98) to collect a multi-species dataset of conifer tree species and common juniper.

The compositional data analysis results show that soil moisture had a weak effect on the plant ionome. However, element log-ratios involving the target element Co in common juniper and Norway spruce were highly affected by the root zone bulk electrical conductivity. These findings highlight the importance of including the soil conditions in the sampling design and using soil electrical conductivity and dielectric permittivity measurements in the data interpretation. The response of plant ionome to bedrock was compared to the geophysical data as a coarse proxy for lithological contrasts between geological domains and to drill core lithogeochemical data as evidence for mineralization. The highly variable bedrock complicated interpretation of results in terms of relating plant ionome to geological domains. However, when compared to bedrock resistivity data, which roughly delineates the mineralized prospects, the plant ionome allowed prediction of sites with high probability for the concealed mineralized bodies at depths of several tens of meters.

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Pathfinder dispersion in fractures above the Oberon gold deposit, Tanami region, Northern Territory, Australia

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The Tanami region in the Northern Territory, Australia is host to abundant gold deposits. However, utilizing surficial geochemistry for exploration remains a challenge as many deposits are under extensive regolith cover, which conceals the geochemical signatures of deposits that reside at depth. The Oberon gold deposit is hosted in a sequence of metasedimentary rocks that have been folded to form a doubly plunging anticline, which is intersected by multiple igneous intrusions. The Oberon gold deposit is atypical, because elevated Au, As, and S anomalies are recorded in surface media. In addition, mineralization is suggested to be covered by approximately 15–30 m of transported cover with recorded seasonal fluctuation in the water table of 5-6 m, with the site flooding during the wet season.

Fracture coatings in drill cores were sampled above the Oberon gold deposit because fractures aid element dispersion at depth by providing permeable pathways through which fluids can move from mineralization into the surrounding rocks and overburden. If these fluids are associated with ore deposit formation or have encountered a nearby ore deposit, they will contain a higher concentration of ore-associated elements than the geochemical baseline. This leaves a distinct mineralogical and geochemical signature on the fracture surface as a coating, which could provide evidence of proximity to mineralization.

Field data shows eight main fracture coatings exist above the Oberon gold deposit, these include 1) Orange; 2) Purple; 3) White; 4) Red; 5) Green; 6) Black; 7) Brown; and 8) Multi-coloured. Based on a subset of twenty fracture coatings, mineralogy consisted of chlorite, kaolinite, white mica, carbonate minerals, smectite, and Fe oxide minerals (goethite and hematite). Bulk geochemical values generated by LA-ICP-MS show elevated pathfinder element contents (As, Cu, Zn, Pb, Bi, Sb, Mo, Se, and Ni) in most fracture coatings in comparison to whole rock geochemical data. Purple, black, and brown fracture types associated with botryoidal goethite, high Fe, and high pathfinder element contents, show the greatest potential as a vector for mineral exploration within the region. This research highlights that fracture coatings record the dispersion of pathfinder elements near ore systems, which enhances the size of the deposit footprint and overall increases the search space for mineral exploration.

Discrimination of porphyry-related epidote using mineral chemistry in the Andes of central Chile

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Epidote is a common hydrothermal mineral in the distal haloes of different types of mineral deposits, particularly in the propylitic alteration haloes of porphyry systems. In the case of deposits covered by pre- or post-mineral rocks and sediments, epidote alteration might be the only visible expression in the field. Recent studies regarding the mineral chemistry of epidote (Cooke et al., 2014) show that, based on the variability of specific REE and trace elements which under certain conditions are incorporated into the epidote mineral structure, it is possible to obtain vectoring information, and also to evaluate the fertility (metal endowment) of the associated hydrothermal system.

It is still not clear, however, if within a specific segment of a magmatic arc it is possible to distinguish, based on epidote mineral chemistry, between epidote related to the distal halo of giant porphyry systems, and epidote with alternative origins (smaller hydrothermal systems, barren plutons, regional metamorphism). Here we evaluate this possibility, based on the results of regional epidote chemistry studies in the late Miocene – early Pliocene porphyry Cu-Mo belt of central Chile. Our results show that there are clear differences in trace elements and REE contents between epidote related to regional metamorphism and to the emplacement of barren Miocene plutons, versus epidote related to hydrothermal systems. Barren Miocene plutons, in particular, do not generate false positives. When considering the epidote related to hydrothermal systems only, it is also possible to distinguish between epidote contained in the halo of giant porphyry systems (El Teniente, Río Blanco-Los Bronces), and epidote related to smaller, but still metal-rich hydrothermal systems. It is concluded that the chemical composition of epidote can be used to differentiate between regional metamorphic epidote, pluton-related alteration, hydrothermal epidote associated with small to medium-size hydrothermal systems and epidote related to giant porphyry deposits, within a single metallogenic belt.

Reference

Cooke, D.R., Baker, M., Hollings, P., Sweet, G., Chang, Z., Danyushevsky, L., Gilbert, S., Zhou, T., White, N.C., Gemmell, J.B., and Inglis, S. 2014. Society of Economic Geologists, Special Publication **18**, 127–152.

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Actinolite as a proxy for characterizing the evolution of Iron-Oxide Copper Gold deposits

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Iron oxide-copper-gold (IOCG) deposits are a globally important source of Cu, Au and critical commodities, including U, Co and REE that are essential to sustain a carbon-neutral society. Despite their relevance, IOCG deposits remain an ill-defined clan, with a range of characteristics that has complicated development of the general genetic model needed to guide exploration for new deposits. Here we focus, for the first time, on the mineral actinolite – an ubiquitous alteration phase in IOCG deposits – We use the chemical variations of actinolite in order to characterize the nature and evolution of the hydrothermal fluids responsible for the formation of the IOCG Candelaria deposit and compare these results with previously published actinolite compositional data from Iron oxide-apatite (IOA) deposits from the Andes. We constructed novel grain-scale maximum temperature formation images by computationally inverting compositional data from X-ray wavelength dispersive spectrometry (WDS) maps. This technique allowed visualization of inferred maximum temperature gradients at a micro-scale within individual actinolite grains. We integrated these results with LA-ICPMS trace element maps of the same actinolite grains showing direct correlation between element zonation and potential temperature of formation.

Results show that Candelaria formed by the superposition of at least two mineralization events with a late Cu-rich fluid overprinting an early, higher temperature, IOA type mineralization event. These distinct events were caused by episodic injections of magmatic-hydrothermal fluids from crystallizing magmas at depth. The higher temperature IOA type-mineralization actinolite in the Candelaria deposit shows distinct chemical signatures similar to lower temperature and later mineralization phases from IOA deposits (e.g. Los Colorados, El Romeral). Our data provide the supports the use of actinolite compositional variations as a novel approach to understand the formation of IOCG deposits and provides a geochemical signature that can be used as a tool for potential vectoring and differentiation between IOCG and IOA exploration.

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Finding a Walton like Zn deposit; a case study using deep penetrating geochemical exploration methods Maritimes Basin, Eastern Canada

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Discovery of new critical metals deposits is dependent on critical geological thinking. In the Carboniferous Maritimes Basin (MB) with 50m + thick cover this is certainly the case. The geochemical response of stratabound mineralisation occurs as low contrast replacement bodies with sharp boundaries. Geochemical studies indicate most surface geochemical methods normally do not penetrate beyond 15m depth. The Enzyme Leach EL refines detection for a significant Cu orebody Canfield Creek at 100m plus depths, with responses to 400m. at Jubilee. At the former Tennycape Mn mine similar conditions are found and acts as a test study for a large potential deposit of critical minerals – in this case Zn. For critical metals an elephant sized Zn deposit in the MB would be expected to be akin to the Walton deposit. In 1940 Walton was discovered – accidentally - when a small surface outcrop of barite was excavated and became an open-pit mine producing barite concentrate. As quarrying progressed the large Pb-Zn-Cu-Ag orebody was found at depth. This orebody was placed into production and from between 1941 until closure in 1955 produced a total of some 4.5 Mt @ >90% $BaSO_4$, 0.413 Mt concentrate with 0.52% Cu, 4.28% Pb, 1.29% Zn and 350 g/t Ag. In situ reserves are estimated at 0.9 Mt barite and 30,000 t sulphide. Comparative analysis to the Irish Lisheen and Silvermines deposit fault systems illustrate the presence of larger scale segments and intervening ramps as ore body bounding structures with intervening small scale segmented fault arrays defining high grade “pods” within the wider deposit. This type of pattern matches closely with what has been noted at Walton and the surrounding area at Tennycape. The former Tennycape Manganese Mine had a war time production of 4,500 tonnes of manganese oxide ore. A 1 km square area was selected for detailed follow-up work following revision of existing soil and till exploration work. Soil data were contoured develop regional scale mapping for the elements Cu, Pb, Zn, Ba, Mn and Fe. The resultant geochemical maps show trends associated with the NW-SE trending Rennie Fault. A large oxidation type low measuring some 700 by 300m in dimension is seen in a reduced chimney pattern similar to the pipe like body of the former producer at Walton. Karst mapping, trenching over an area showing weakly mineralized Mn oxide float, a 1.2 km sq gravity survey with a follow up 190 soil sample over a 100 X 100 m grid was completed. 3 separate partial extraction techniques were tested including EL, Hot Hydroxylamine (HX) and Spatiotemporal Geochemical Hydrocarbons (SGH) and Trenches 1 to 4 in weakly mineralized float. The 800m trenching work revealed bedrock like boulder basement with large local angular slabs, chunky boulders and rough cobbles of mineralized Macumber/Pembroke Limestone. An impactful Combination

Anomaly of significant size is seen – of equal size to that over a typical buried Por Cu in the Atacama Desert of Chile. The anomaly at Tennycape is also the largest seen so far in several EL studies in Nova Scotia. The Tennycape Oxidation Cell is seen as a 600m x 400m trending NW to SE from 501100N to 501400N and 430600E to 431200E low in the centre of the grid as anomalies in Cl, Br, Ba, Se, Ge, Ti and Mn. The EL Halogens Cl and Br define a distinct cell with Se, Ge, and Ti as additional definers. except Ba that occurs as a distinct trough – possible fault/plumbing trace Ba seems to be a law unto itself as a large distinct trough body trending at the side of the main anomaly. This is a typical association with critical metals seen in the MB. The critical metals As, V, Cu and Ga define the target with the Base Metals in Halo – viz Pb, Zn, Cd, Co, and Ni. The REE of La, Ce in addition to Th and U form spatially coherent high in West – a possible intrusive body? The gravity survey also delimited the extent of the probable reduced chimney also outlined by the EL hydride As. HX results closely align with the local faulting associated with the Rennie Fault while the SGH Alkyl-Alkenes have 3 apical anomalies associated with the central low of the redox cell. The area is ready for additional drilling – vertical RC open holes are the most cost-effective option for the central halogen outlined low.

Geochemical Exploration for Critical Metals in The Carboniferous Maritimes Basin, Eastern Canada

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Critical minerals are presently defined as those mineral resources essential to the economy and whose supply may be disrupted. The 'criticality' of a mineral changes with time as supply and society's needs shift. In the Maritimes Basin (MB) more recent application of deep penetrating geochemistry has aided in exploring for critical minerals by comparison to the more the active Irish Orefield. Faulting is the most important control on mineralisation. Results are presented from representative deposits at Gays River Pb-Zn to 100m at Canfield Creek Cu and 400m anhydrite at Jubilee Zn. The Gays River limestone hosted Pb-Zn has high-grade mineralization in a massive sulphide zone 0.1 to 5.0m thick with up to 7.8 % Pb and 5.7 % Zn in a footwall up to 12m thick. Locally disseminated mineralization (>2% Zn equivalent) extends up to 20m into the footwall. An Enzyme Leach EL over sub cropping reefs 2 km to SE of main deposit reveals a large circular feature as a bioherm or structural high. The area has a low-level response correlated with the presence of disseminated ore. Lows identified are reflecting a greater concentration of reducing sulphide and therefore of higher-grade areas. The massive ore zone or Trench is detected as a sinuous North to South trending series of Oxidation Lows running along the axis of the buried reef area. The Canfield Creek Cu-Ag deposit occurs at a depth of 100m beneath a bedrock cover of surficial and clastic sediments. The ore zone is about 5m thick with projected reserves of 300,000 tons of 1.2 % Cu and minor Ag calculated from 27 drill holes. Multimedia geochemical survey shows a very low response in most surficial media with a barely recognizable response in till for Cu and Balsam Fir and also Ag in humus. EL outlines a dominant NW trending structure. The Jubilee Zn-Pb Deposit is found in 3 main zones 6 to 16m wide in WindsorGroup basal carbonate associated with an active growth fault in and extensive brecciation containing 2.5 mt of 4 to 5% Zn. The deposit is well controlled by drilling with zones up to 250mwide with associated hydrocarbons. The multimedia study was conducted on soils on 3 lines over the deposit at outcrop, 40m burial and 350m burial with depth controlled by drilling. At surface vegetation was taken on using a 500m grid with Red Spruce twig and bark and Balsam Fir twig taken from the immediate deposit area. A "total" 4 acid extraction and Enzyme Leach analysis was compared in the soils at surface, 40m burial and 350m below surface. Results were varied with well-defined anomalies in Ni, As, Co, Pb, Zn and V at outcrop. The 40 m burial only has peaks for Zn and Ba. The 350m burial had almost no recognizable response - muted Zn, Ba, Ni and Co. Enzyme Leach had surface Apical anomalies in the Halogens, As, Pb, Zn and Co with a 200m Halo of Rb, Sr, Mo, and Ba as lows. Line 2 (40m burial) has Anomalies in the Halogens, Zn, Cd, Mn, Ga, Pb and Sb plus a 600m halo in Rb, Ti, Sn, Li, Cu, Zr, Y, La, Ce, Sm, Th, Nb and Sc. Lastly Line 1 (350m burial) has Apical anomalies in La, Ce, REE, Sc, Ti and Ba plus As, Sr, Cd, Co, Ni, Cu, Zn and Zr in the halo.

Oral Presentations

Technical Session 2

New field portable technologies: Improving the analysis and turnaround times in exploration

A population-based approach to pXRF calibration to provide near-time lithogeochemistry for guiding drilling decisions at Carlin-type gold projects

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Exploration in Nevada is transitioning towards targets that are deeper and under cover - especially in the case of the Carlin-type gold deposits (CTGDs) that represent the majority of Nevada's gold endowment. In addition to the challenges and costs associated with drilling deep covered targets, exploring for CTGDs is further complicated by the fact that many features of significance in Carlin systems are indistinguishable visually. Establishing whether a drillhole has intersected a targeted stratigraphy regularly requires multi-element pathfinder and litho-geochemical data. The limits of detection of modern pXRF instruments suggest their suitability to provide such timely data as inputs to guide drilling decisions.

As part of setting up a pXRF-derived geochemistry workflow to support its drilling programs, Nevada Exploration completed an orientation program comparing pXRF and 4-acid data at an active drilling program to consider sample preparation, reading intervals, reading times, and calibration. Due to the intense heterogeneity within the lithologies of interest, the orientation program highlighted significant challenges surrounding both sampling strategies and calibration.

The program established that collecting readings from simple half core samples every 2.5 feet down hole using three minute read times provided raw outputs that once filtered using a running three-sample average closely followed the trends and variability (highs, mediums, and lows) of the 4-acid data. Having generated fit-for-purpose raw data, Nevada exploration next considered calibration strategies with the goal of providing semi-quantitative data suitable for more-advanced geochemical interpretation, such as element ratios and enrichment factors.

Taking a traditional regression-based approach to calibration proved ill suited due to the heterogeneity of the units of interest. Instead, Nevada Exploration developed a project-specific set of correction factors by taking a population-based approach more commonly used in the biological and health sciences known as histogram matching. The resulting corrected pXRF data closely match the 4-acid derived data for important elements of interest.

Today Nevada Exploration is using the semi-quantitative pXRF data provided by this unconventional approach to calibration to cost-effectively provide a diagnostic suite of elements to identify major stratigraphic units in near time that are directly support drilling decisions at its current projects.

Cathode to phyllode via *in situ* mode - Field use of pXRF to analyse pine needles in regional and deposit scale geochemical mapping in the Cobar Basin

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There have been few regional geochemical mapping programs using vegetation as the primary sampling media. At the deposit scale, the use of biogeochemistry has received more attention, but studies are rare compared with those involving regolith materials.

A series of deposit and regional scale biogeochemical studies has recently been conducted in the highly mineralized Cobar Basin of NSW, other parts of the Lachlan Fold Belt and in Cyprus. Sampling has generally been restricted to species of *Pinus* given their capacity to take up a wide range of metals without suffering the effects of metal toxicity or presenting barriers to uptake. Strong biogeochemical responses have been observed in the needles over a range of deposit types (Au, Cu-Pb-Zn, Ni-Co) with low background values. This has included multi-element (including W, Pb, Au, REE and Re) anomalous patterns over mineralization buried under transported cover. The only element for which responses are typically subdued is Cu, indicating strong controls on uptake.

The advantages of obtaining real-time geochemical data, especially in remote areas, and the cost advantages in the use of methods such as pXRF has prompted a comparison between in-situ and lab-based analyses, and pXRF versus ICPMS. For many elements there is high correlation between these methods and between in-situ and lab-based pXRF measurements.

Financing: This project is partly funded by the MinEx CRC and the remainder by exploration companies.

New applications of Portable XRF (pXRF) in mineral exploration

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Users of portable XRF (pXRF) continue to demonstrate incredible innovation in the application of this now ubiquitous exploration tool. Whilst manufacturers attempt to implement the latest technology into the hardware and software of portable XRF's, it is the users of the technology who drive genuine innovation by finding new ways to use the instruments and implement these ideas into exploration programs. This talk will present real world case study examples of the application of portable XRF in ways not previously considered prior to the last IAGS. The talk will summarise the most recent **generic** developments of this technologies application in mineral exploration. It will touch on innovation and developments in vegetation analysis, inclusion of pXRF on various automation systems and robots including (but not limited to) core scanners as well as developments in 3rd party software and workflows to control pXRF QA/QC and data management. The talk will also present information on new developments to be able to measure Au to approx 20ppb with pXRF as well as the latest developments in addressing low level cobalt in the presence of problematic associated Fe and Ni peaks and discuss the use of portable XRF for Lithium. New techniques for pXRF calibration will be discussed from innovative work on drill core to provide quantitative data on chemo-stratigraphy in order to make near real time drilling optimisation decisions. The talk will aim to collate the latest innovations in pXRF application since the last IAGS and show case studies in all instances.

Comparative pXRF and ICP ES/MS data for regional till samples: East Arm of Great Slave Lake, NT, Canada

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The Geological Survey of Canada undertook a mineral resource assessment for a proposed national park in northern Canada (~ 33,500 km^2) spanning the transition from boreal forest to barren lands tundra. Bedrock geology of this region is complex and includes the Archean Slave Craton, the Archean and Paleoproterozoic Rae domain of the Churchill Province, the Paleoproterozoic Thelon and Taltson magmatic-tectonic zones, and the Paleoproterozoic East Arm sedimentary basin. The area has variable mineral potential for lode gold, kimberlite-hosted diamonds, VMS, vein uranium and copper, SEDEX, as well as other deposit types. A comparison of analytical methods was carried out after processing the field collected samples to acquire both the < 2 mm and for the < 0.063 mm size fractions for 241 surficial sediment (till) samples, collected using a 10 x 10 km grid. Analytical methods comprised:

1) aqua regia followed by ICP-MS analysis,

2) 4-acid hot dissolution followed by ICP-ES/MS analysis,

3) lithium metaborate/tetraborate fusion methods followed by ICP-ES for major elements and ICP-MS for trace elements and,

4) portable XRF on dried, non-sieved sediment samples subjected to a granular segregation processing technique (to produce a clay-silt proxy) for seventeen elements (Ba, Ca, Cr, Cu, Fe, K, Mn, Ni, Pb, Rb, Sr, Th, Ti, U, V, Zn, and Zr).

Results indicate that pXRF data do not replicate exactly the laboratory 4-acid and fusion data (in terms of precision and accuracy), but the relationship between the datasets is systematic as displayed in x-y scattergrams. Interpolated single element plots indicate that till samples with anomalies of high and low pXRF concentration levels are synonymous with high and low laboratory-based analytical concentration levels, respectively. The pXRF interpolations thus illustrate the regional geochemical trends, and most importantly, the significant geochemical anomalies in the surficial samples.

These results indicate that pXRF spectrometry for a subset of elements is comparable to traditional laboratory methods. pXRF spectrometry also provides the benefit of rapid analysis and data acquisition that has a direct influence on real time sampling designs. This information facilitates efficient and cost-effective field projects (i.e., where used to identify regions of interest for high density sampling), and to prioritize samples to be analyzed using traditional geochemical methods. These tactics should increase the efficiency and success of a mineral exploration and/or environmental sampling programs.

Field analysis of low level gold using novel detectORETM technology

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We describe a new method to analyse for Au at low ppb levels in the field using a portable X-Ray fluorescence (pXRF) machine. The pXRF machine has been used increasingly since its development about three decades ago and provides fast, non-destructive elemental analysis in a vast range of applications including those used by mineral explorers. However, while pXRF can be used to analyse many elements at concentration levels relevant to mineral exploration eg Cu, Pb and Fe, it is not feasible to analyse for Au directly in samples at typical concentrations encountered in the field e.g. 1 ppm or lower. The pXRF machine can detect Au above ~5 ppm but only when the concentration of other associated elements (eg As, W and Zn) that interfere with the Au X-ray peaks are low. Until now, these limitations have prevented the adoption of pXRF for Au applications except for jewelry, scrap metal or nuggets. However, patented detectORE™ technology (using a pXRF, a process and special software) can measure Au in samples at the low ppb range e.g., 6% and 1% relative standard deviation at 5 ppb and 1000 ppb, respectively. Quantification of Au by detectORE™ technology is achieved through a digestion and concentration step that raises Au to detectable concentrations on a collector device while excluding the interfering elements. The standard curve is linear over a wide concentration range (2–10000 ppb) and has been tested on CRMs and many exploration samples from a wide range of deposits both in the field and laboratory. DetectORE™ does not give a total Au analysis like fire assay or neutron activation analysis but generates fit-for-purpose geochemical Au data in the field. Gold analyses acquired during a soil sampling or drilling campaign on-the-fly allows the geologist to make critical decisions on where further samples are to be taken which is termed Reactive Sampling™. Dynamic Au exploration brings increased value to resource-limited small to mid-sized companies. Currently, mineral explorers may have to wait weeks or months before the results of Au analyses are reported to them by the analytical laboratory – especially if they are operating in a remote location or services are in high demand. The do-it-yourself detectORE™ process is safe to use and 4WD-portable. About 100–200 samples per day per person is achievable with the method scalable to higher volumes. As a result of detectORE™, Au deposits may be found faster reducing the overall cost of exploration.

Getting the most out of real-time portable XRF; The TruScan Solution

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A result of the current exploration boom has been the significant increase in lab turnaround times, putting additional pressure on geology teams. Resulting in the complete debilitation of some operations where programs are pushed back or even halted to allow assays to "catch up" and instruct the explorers on how best to proceed. Teams have found ways to deal with this, but in many instances the solutions have been suboptimal.

However, optimal solutions can be found with the use of purpose-built on-site XRF scanning: TruScan. TruScan is a mobile trailer that can be easily transported anywhere, and by means of proprietary technology executes a non-destructive continuous XRF scan with dynamic conditions customized for each site. This process provides several benefits; it eliminates manual sampling bias, reduces error by shortening the chain of custody, provides near real-time insights, and streamlines the collection of geochemical data, all whilst achieving accuracies in-line with laboratories for many elements. This is made possible by TruScan's proprietary calibration process leveraging a combination of site optimized scanning conditions and state-of-the-art normalization, deconvolution, and machine learning driven corrections and correlations. Use of site-specific standards is leveraged to deliver both analyses of common XRF analyzed elements and those that lie beyond the detection range of other systems.

TruScan's accompanying intuitive software package processes the data in real time and allows for its visualization and analysis from anywhere in the world. The package offers automated additional features such as capturing HD images of wet and dry core, processing structural data such as RQD, and classification and orientation of structures.

This combination of features allows real-time data delivery to the geologists and grants them the ability to optimize meters drilled by terminating or extending holes with confidence along with providing insights on drillhole optimization throughout a program. In most instances, modeling can be brought forward with any laboratory assays only being done for reporting purposes. This allows for quantitative auto-logging, reducing the impacts of staff turnover as well as the ability to quantify alteration intensity and even look through pervasive texturally destructive alteration to the original lithology, providing further vectors during the campaign. In essence, TruScan can optimize exploration.

Financing: Boart Longyear.

Rapid and robust: An assessment of Handheld XRF in the field settings

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Time-sensitive decisions based on robust data underpin successful mineral exploration and mining operations. While most operations rely on bulk techniques with turn-around on results often at days or weeks, the introduction of portable analytical tools, such as handheld X-ray Fluorescence (HH-XRF) allows rapid analysis and characterization on scales smaller than possible by bulk techniques. However, the generation of robust data sets from HH-XRF requires an understanding of appropriate sample preparation, use of quantification tools, and acknowledgement of technique limitations. We present two case studies that demonstrate the proven potential of HH-XRF as a rapid and reliable geochemical tool.

In the first case study, we present data from a 170 m drill hole from the Eskay Creek volcanogenic massive sulfide deposit, Northwestern British Columbia (Canada), which hosts high-grade Gold-Silver mineralization. In situ HH-XRF core logging results show strong correspondence of indicator element concentrations compared to bulk geochemical assay data obtained by inductively coupled plasma-mass spectrometry.

In the second case study, we present an in-mine grade-control study where HH-XRF has been used to evaluate the quality of gypsum. HH-XRF analyses made directly on heterogeneous rock samples from the quarry was able to reproduce SO_3 results from the bulk thermogravimetric analysis, where samples were powdered and homogenized, in about half of the samples. Deviation in the other samples indicates heterogeneity in sample materials at the scale of the HH-XRF spot, indicating the need for appropriate sample preparation, or an approach such as averaging of higher numbers of HH-XRF spot analyses.

These two HH-XRF studies suggest that with an appropriate approach to data collection HH-XRF can provide reliable geochemical results in the field allowing rapid decision-making during drilling campaigns, or in the mine for robust grade control purposes.

Re-inventing the laboratory for the digital age: high resolution XRF core scanning to characterize the distribution of critical metals

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As the mining and exploration industry undergo digital transformation for improved value creation there are increasing demands for faster analytical data that underpin operational decision-making. Developments in electronics, instrumentation and data handling have led to the re-assessment of how analytical data can be delivered. The SGS FAST program based on robust field portable technologies such as pXRF and FTIR, and automated XRF core logging, generates rapid fit-for-purpose chemical or mineralogical data at site that can be uploaded within 24-48 hours to modeling software or machine learning routines for improved exploration targeting, ore characterization and mine planning activities.

While XRF continuous core scanning instruments have been available since the early 2000s their application in mineral exploration has been limited. There has been greater adoption of hyperspectral core scanners with the use of VNIR-SWIR cameras to document changes in alteration mineralogy as a vector to ore. However, not all mineralised systems are alteration driven. For many there are geochemical gradients that can be used as a vector to ore Nowhere is this truer than in exploration for critical minerals such as lithium, vanadium, nickel, niobium, and the rare earth elements (REE) where the petrogenetic evolution leading to metal concentration can be quite intricate and our current models for their occurrence are not as well developed as they are for metals such as copper and gold.

The aim of this presentation is to describe the Minalyze high resolution XRF core scanning system with its multiple outputs and its application in an early-stage Cu-Au exploration program conducted by VR Resources at the Hecla-Kilmer multiphase alkaline intrusive system with carbonatite in northern Ontario. The early results indicate a complex polymetallic mineralization of which the most potentially valuable might be REE and critical metal concentrations that include niobium.

Financing: SGS Canada Inc. VR Resources Ltd.

Oral Presentations

Technical Session 3

Big data: squeezing multi-element geochemical data by means of data science and self-learning techniques

Mineral Resource Prediction Using Advanced Data Analytics and Machine Learning Based on Stream Sediment Geochemical Data, British Columbia

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Regional geochemical survey (RGS) stream sediment geochemical data from British Columbia were used to create predictive maps of specific types of mineral deposit. The geochemical data were levelled for laboratory analytical effects and values reported at less than the lower limit of detection were imputed to minimize statistical bias. The data were then adjusted using a centred log ratio transformation to moderate the effects of geochemical closure. The data were processed using principal component analysis (PCA) and t-distributed Stochastic Neighbour Embedding (t-SNE). PCA provides a reduced number of dimensions in which the variability of the data is expressed in terms of linear combinations of the log-centred transformed variables and commonly reflect processes associated with lithologies, alteration and mineralization. t-SNE is a non-linear metric of association of the data based on the probability association of neighbouring points.

We present the results of a resource mineral deposit model prediction for a region in British Columbia. Each stream sediment sample site was attributed with the closest MINFILE occurrence, excluding anomalies and showings, within 2.5 km of the sample site. MINFILE occurrences were grouped based on similarities in the British Columbia Geological Survey mineral deposit models. A training data set comprised of stream sediment samples with MINFILE attributes that do not include anomalies or showings and are less than 2.5 km distant was created. An additional group of 100 stream sediment analyses that do not have any mineral deposit affiliation were included as part of the training set. The remaining data were used as the test dataset.

The application of PCA and t-SNE metrics to characterize the nature of the stream sediment geochemistry and the association with the mineral deposit models was tested using the predictive method of random forests (RF). The resulting posterior probabilities were kriged and imaged to show areas where increased potential exists for a given mineral deposit model. The MINFILE occurrence locations and the predicted classes were plotted on the resulting image maps. For many of the mineral deposit types, the presence of the known MINFILE occurrences show a close geospatial association with the predicted classes and areas of increased posterior probability. We present the results of several mineral deposit models and suggest that this method of resource prediction has global application.

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Rapid Estimator of geometallurgical variables based on hyperspectral images and a Bayesian processing scheme: methodology and case studies

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A methodology for the estimation of geometallurgical variables on mineral samples of different physical characteristics is presented. The training and processing flow of the algorithmic method that makes possible the estimation on new samples is described. The method is based on a Bayesian and hierarchical scheme, which has as its main element the use of the multi-pixel characteristics of the data and the full spectral range available and no specific spectral absorption, i.e., it is not based on feature extraction. The processing flow is composed of two stages, a spectral clustering stage and a regression stage, which represents a hierarchical regression schema. A set of case studies is also described in which the method is applied on different groups of mineral samples and different variables to be estimated, such as quantitative mineralogy for several minerals, geochemistry, work index hardness, liberation grades of certain minerals by size fraction, among others. These sample sets come from different geological contexts and have been characterized by standardized laboratory analysis, which provides training and validation information for each case study. The value of this applied research is highlighted as a contribution to the creation of predictive control strategies for metallurgical processes such as flotation since the method allows estimating variables quickly and with an error very similar to that of laboratory methods.

Using machine learning to facilitate the analysis of multi-element geochemistry datasets in the Abanico and Farellones formations in Central Chile (32°-33°S)

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On the Chilean side of the Principal Cordillera of the Central Andes at 32°-33°S, most of the rocks (dominantly arc volcanics) correspond to two Cenozoic units, the Abanico and overlying Farellones Formation, representing a tectonic extension (~40-20 Ma) and subsequent inversion (~20-5 Ma) of a retroarc basin. The precise stratigraphic location of the boundary between these phases can be difficult to identify due to deformation, lithological similarities, and lateral variation of the units. The tectonic transition is however, apparent geochemically in the progression from the more tholeiitic tending rocks of the extensional phase (Abanico Fm.) to the more calc-alkaline rocks of the inversional phase (Farellones Fm.). However, the effort to elucidate clear geochemical markers to distinguish between these two tectonic periods has proven difficult given the temporal and compositional continuity between the two. Here, we use supervised and unsupervised machine learning methods to identify cryptic geochemical tendencies in a multi-element dataset of 29 samples from the Abanico and Farellones formations. The samples were preliminarily classified as Abanico Fm. (AF) or Farellones Fm. (FF) based on published age data as well as the La/Yb vs. Nb/La plot, as past studies have identified an observable separation between these formations in these elements. The XGBoost library was then used to build a binary classifier model with the pre-classified samples from AF and FF and using 44 major and trace element variables. The two elements that had the highest impact on the model according to the SHAP values generated were P2O5 and MnO. When plotted with these variables, there is an observable separation between the AF and FF groups, implying that there could be a correlation between P2O5, MnO, and the transition from a tholeiitic to a calc-alkaline arc. We also performed a dendrogram cluster analysis with all 44 elements and 29 samples with no prior classification as AF or FF. The algorithm identified 2 major groups with one of them being composed of two minor groups. While each of the major groups correspond dominantly to AF and FF, there is minor representation of both formations in each major group. This analytical workflow could be applied to future geochemical studies in the Principal Cordillera of Central Chile and could lead to further insight into the dynamics of the transition from an extensional to inversional basin system.

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Multi-digestion regional rock geochemistry of Variscan granites and elvans in SW England: delineation of composite intrusions and Sn-Li potential

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Granites are known to host and be genetically linked to the formation of tin and lithium deposits in SW England. Elvan (quartz-porphyry/ rhyolite) dykes are closely linked, spatially and temporally to Sn-base metal veins but slightly younger than comparable granites. The composite nature and detailed systematic geochemistry are less well known for both.

Multi-digestion (fusion, 4 acid, aqua regia) was coupled with XRF, ICP-ES/MS and IC finishes on ~ 350 regional rock samples of granites and elvans.

PCA and machine learning confirmed the classification of granites of Simons et al. (2016,7) into 5 groups mainly based on trace elements. Lithium enrichment in granites (and potential) is strongly correlated with F, both in G4/5 (Li-mica, topaz) as well as, more weakly, in G2 (muscovite) granites, which host greisen Sn-W deposits. There is also correlation of F with W and Ta, in G4/5 although only disseminated Sn-W mineralisation is known. Boron is enriched in G2 and G5 but most strongly in G4. Chlorine is enriched in G3 granites, notably Dartmoor and Land's End, and strongly depleted in greisened granites. There is no enrichment of background granites in Sn.

The elvans are for first time shown related to both G1/G2 and G4/G5 granites, based largely on Nb/Zr ratios, although Ni and REE indicate intrusion of some may have been driven by lamprophyres. Several of the G1/G2 ungreisened elvans are strongly enriched in Sn. In contrast some G4/G5 elvans are enriched in Li-Ta-Sn-F and are geochemically similar to aplite/ pegmatites. The chemistry of elvans is proposed to indicate the location of operation of subsurface mineralising processes, and hence potential.

Multi-digestion high sensitivity analyses are required to delineate differing granite phases and areas of associated hardrock tin or lithium potential.

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Gold recovery prediction using geostatistical and machine learning tools

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Nowadays, mining operations measure different minerals and geometallurgical variables in their feed, concentrate, and tailings. However, the result of such measurements tends to be ex-post, so any feedback of this information into the work of the processing plant is more of a reactive nature. At present, metallurgical recovery is generally used as a post-operational variable (KPI), in which the processing plant reacts only using expert knowledge, lacking predictive capabilities. Mine planning can account for better scheduling of the feed, but to have those geometallurgical variables in-situ, such as recovery and grades, could be difficult to incorporate into a block model due to high costs in metallurgical assays and complex modeling. The use of a predictive model that incorporates different data sources such as the block model, geological information, and drillholes, could allow the optimization of the processing plant, based on an improved characterization of future metallurgical recovery. In this work, a model integrating Geostatistics, Machine Learning and Stochastic Simulation tools was developed to obtain a prediction of metallurgical recovery using the historical data of a polymetallic deposit and one year of processing data. Our prediction

model uses an in-house high-performance geostatistics tool and a spatial block sequencing algorithm to organize mine planning according to raw operational scheduling. Subsequently, a temporal processing unit was designed that correlates mine data with plant data, which serves as input for a Machine Learning model that relates the different available data to the metallurgical recovery of the flotation stage. Finally, a Monte Carlo simulation scheme is used that provides several future scenarios, a confidence bandwidth, and the prediction of the gold recovery, with which it is possible to build a block model with the estimated recovery and gold grades. As a result, a distribution of scenarios for two weeks in the future was obtained, which allows to have a better estimation of the metallurgical recovery. The Machine Learning model obtains a Spearman correlation greater than 0.85, and the metallurgical recovery estimation in the block model improves between 5-10% the Mean Absolute Percentage Error (MAPE) for different cases of prediction. Additionally, an expert validation was carried out, which considered the opinion of different people linked to this operation. As a future work, the aim is to continue validating the model for different time periods, as well as to include a greater number of variables that provide more information in the characterization of the process.

New technologies capable to optimize the big-data generated in exploration; The symbiotic case of TruScan and TruVision

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The boom of new technologies in the mining industry has generated an abundance of data of such magnitude that makes it very difficult to make the best use of so much information, resulting in an underutilization of the most valuable thing in an exploration campaign, the information of what is under our feet.

In this context, big-data tools and techniques have emerged to make the most of this abundance of data, whether in terms of geophysics, structures, rock mechanics, multi-elemental geochemistry, etc.

An example of disruptive technology in mining exploration is TruScan -Boart Longyear's proprietary technology-, which consists of a mobile chemical laboratory that allows obtaining the geochemistry of rock cores or RC in real time, as well as obtaining high-resolution photos of dry and wet samples. The geochemistry is obtained by X-ray fluorescence (XRF), applied directly on the rock, to which sophisticated machine learning techniques are added to broaden the base of quantifiable elements, adding elements that due to their low concentrations until now were not quantified using XRF. This allows us to obtain geochemical results of more than 80 elements, with a detection limit of less than one ppm, without the need to alter the samples, nor having to send them long distances, since TruScan can operate in any terrain, whether next to a drilling rig, loggers, mine, etc.

The abundance of TruScan acquired data requires a tool that allows geologists to visualize, process, analyze and use these data. To solve this problem, Boart Longyear has created a useful tool called TruVision -Boart Longyear's proprietary technology- that facilitates the analysis of this abundant data.

TruVision allows simple visualization of elemental concentrations along cores, generation of chemical ratios, identification of alterations, correlations between elements, gradients, vectoring, discovery of lithological changes, core logging using machine learning, among many other applications, greatly facilitating exploration, opening a world of opportunities.

New technologies produced by Boart Longyear make it possible to deal with the increasing difficulty of discovering new deposits. In areas with decades of traditional exploration, the only way to achieve new and better results is to use state-of-the-art technology that allows us to see what we never could before.

Financing: Boart Longyear

Petrology & Lithogeochemistry of the Wildcat Brook Mo-W deposit, Charlotte County, New Brunswick, Canada: Insights into Log-Ratio Analysis

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The Wildcat Brook Mo-W deposit is located approximately 9 km east of the former Mt. Pleasant Sn-W-Mo mine in Charlotte County, New Brunswick. It is hosted by a leucocratic, quartz-feldspar porphyritic-to-aplitic, peraluminous, EW-striking, moderately north-dipping dyke. This intrudes turbiditic metasedimentary wackes and argillites of the Digdequash Formation of the Fredericton Trough immediately north of the Magaguadavic granite of the St. George batholith.

High-grade Mo mineralization up to 4 % over one meter occurs in two niches: (i) molybdenite blebs up to 4 mm in diameter disseminated in small miarolitic cavities within albite- and muscovite-altered dyke, and (ii) medium-grade Mo mineralization at the margins or cores of 2-5 cm wide quartz veins cutting altered or un-altered dyke and adjacent metasedimentary rocks. Wackes adjacent to the dyke also contain up to 2 cm diameter rare white orbs of radially-arrayed acicular crystals of powellite ($CaMoO_4$) replacing the matrix and clastic grains. At present, the dyke has been intersected by 17 diamond drill cores spanning approximately 250 m along strike and dip. Dyke thickness ranges from 17 to 42 meters (averaging 27 m thick), and the dyke contains a sample length-weighted average grade of 0.27 % Mo.

Two styles of hydrothermal alteration occur in the dyke: albite, and muscovite-quartz. Molar element ratio (MER) analysis of 110 drill core samples, constrained by petrography, reveal that the addition of Na and loss of K and Ca accompanied albite alteration: Microcline + Na^+ => Albite + K^+ (-8 vol. %) & Anorthite + 4 Quartz + 2 Na^+ => 2 Albite + 3 Ca^{+2} (+4 vol.%), and the addition of K and loss of Na accompanied muscovite plus quartz alteration: 3 Albite + K^+ + 2 H^+ => Muscovite + 6 Quartz + 3 Na^+ (-7 vol. %). These alteration styles principally affect the dyke, but several greisenized hydrothermal compartments up to several meters width, bounded by quartz veins and containing coarse muscovite, quartz, and minor Mo mineralization, occur above the dyke.

Clearly, the alteration styles recognized in the dyke displace rock compositions on MER diagrams linearly, and so when plotted in logarithmic space, as log-ratios, the patterns become decidedly non-linear, complicating interpretation. Furthermore, use of linear statistical procedures, such as principle components analysis, on log-ratios is numerically invalid, and is not an effective way to understand the causes of compositional variations in rocks.

Conserved Element Ratio Analysis in Lithogeochemistry: From Scatterplots to Spider Diagrams

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For many years, mathematicians have warned geoscientists that data consisting of proportions of a whole suffer from the obscuring effects that closure, the constraint that compositions sum to unity, imposes on element (and mineral) concentration data. In 2018, Stanley illustrated that while closure exists in all element compositions, its impact is small and can be ignored: (a) amongst most trace elements, (b) amongst elements whose material transfer is large relative to changes in system size, and (c) amongst elements involved in exchange processes. However, where it exists (*e.g.*, in most major oxide concentrations), closure can be avoided by investigating the ratios of the concentrations.

Effectively avoiding closure in concentration data requires knowing which elements are not involved in material transfer (conserved elements) and which are (material transfer elements). If a concentration ratio is composed of two conserved elements, this ratio will not vary, given measurement error, regardless of how much material transfer occurs. As a result, ratios of conserved element concentrations represent an ideal tool for recognizing related rocks, and classifying them into distinct groups (lithologies).

Conserved element ratios can be examined for the above traits using a variety of simple diagrams, including: (i) scatterplots, (ii) ternary diagrams, (iii) ratio diagrams, and (iv) spider diagrams. Each of these diagrams requires a different interpretation method because they exhibit different behaviors, but all are founded on the same principle. With knowledge of the effects of material transfer and closure on these diagrams, and after propagating measurement errors onto them, a simple geometrical criterion, that data lie on a line given measurement error, can be tested to assess group membership. This allows geoscientists to perform rigorous hypothesis testing of suites of rocks, and to develop a chemical classification of different lithologies (a chemostratigraphy). This can be compared with an independently assembled lithostratigraphy to truly understand the nature of the various rocks in a database.

Financing: Unsupported research

Integration of Texture and SWIR Spectroscopy with Geochemistry to Improve Machine-driven Classification of Geological Characteristics

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Multi-element geochemistry has increased in importance in the mineral exploration sector in recent years (Gazley, 2018; Halley, 2020). Workflows typically involve grouping numerous analyses based on bivariate plots or ternary diagrams of elements relevant to the problem at hand and relating those groupings to a particular geological classification. However, a persistent weakness of any geochemical approach to classification is found in its inherent textural blindness. In other words, the inability of geochemistry to distinguish between texturally distinct rocks where chemical compositions are not sufficiently distinct. We address this problem by using computational methods to extract empirical textural features from photography and merge them with spatially coincident portable X-ray fluorescence (pXRF) compositional and short-wave infrared (SWIR) spectroscopy data to improve upon semi-automated classifications.

The studied dataset consists of 4462 datapoints taken at 2 m intervals from 12 diamond drillholes from an Andean porphyry-epithermal system (Pimenton). Pimenton is located 115 km NNE of Santiago, Chile, in the Late Miocene to Early Pliocene porphyry belt (Perello et al., 2012) nearby to deposits such as West Wall, Novicio, and Vizcachitas in the “San Felipe Cluster” (Toro et al., 2006). Usage of infield data acquisition techniques enabled a large amount of data collection to be rapidly carried out by unskilled labor and facilitate robust reclassification of the drill-core in terms of lithology and alteration.

Lithological classification using a random forest (Breiman, 2001; Ho, 1995) algorithm applied to the Pimenton dataset shows that using pXRF data to distinguish between andesite and diorite porphyry produces an accuracy of 82%, using photographic textural data produces an accuracy of 84%, and combining both compositional and textural input features produces an accuracy of 88%, a significant improvement. Examination of feature importance for the integrated classifier shows a mixture of composition and first- and second-order textural characteristics informing the classification, confirming their complementary nature. Further work involving the integration of SWIR inputs to classifiers for alteration will be presented, supporting the hypothesis that rapid infield data acquisition, data integration, and ML classification techniques can provide useful outcomes for high-volume drilling operations.

Financing: Department of Geological Sciences and Geological Engineering, Queen’s University, 36 Union Street, Kingston, Ontario, Canada, K7L 3N6

Oral Presentations

Technical Session 4

Geochemistry applied to mineral characterization for geological, geometallurgical and resource modeling

Transformational Ore Body Knowledge Workflows: The data behind the vision

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A variety of drill core scanning technology is currently on the market, each with a suite of sensors delivering different data products such as X-ray transmission, X-ray fluorescence, hyperspectral, magnetic susceptibility, RGB imagery, and more. These datasets have great potential if interpreted using the appropriate domain expertise of geoscientists. A critical practical goal is rock characterization and geological modelling to enhance ore body knowledge, inform exploration targets, further automate machine-assisted core-logging, create predictive early-stage or dynamic grade-estimation, guide geochemical and geometallurgical sample selection, and yield improved 3D models (geology, geotechnical, resource grade, structure, and so on). However, significant gaps in most workflows prevent this technology from effective use.

Core scanning data products offer two typical benefits for users: 1) high resolution results, on millimetre or centimetre scale; and 2) rapid collection which can be integrated with existing logging and sampling practices. An issue is that the hardware and analytical instrumentation underpinning these scanning technologies are still emerging fields, from both a mechanical and physics perspective, and in analytical performance (e.g., accuracy, precision), which is not being routinely evaluated by the industry. Currently, use of conventional quality assurance and quality control (QA/QC) metrics based on certified reference materials, blanks, and sample duplicates are notably absent except when demanded by clients. Therefore, accuracy and precision need to be evaluated by retrospective calibration to other datasets, months after data collection by, for example, compositing continuous XRF intervals to commercial laboratory assay lengths.

To address this gap, we demonstrate the value of developing a robust data validation workflow to measure the performance of rapid-analysis scanning tools with every box scanned. This includes quantifying analytical error, sampling error, assessing natural geological variability, and defining practical detection limits. We conclude that it is imperative for geochemists to be involved from the earliest stages of scanning technology trials through to implementation. By working in collaboration with service providers and site-based teams, we are observing the beginnings of transformational mining and exploration workflows, integrating quantitative data and domain knowledge to generate dynamic models that de-risk our assets.

Financing: Teck Resources Limited

Alteration Zonation Patterns Characterized by Hyperspectral Data within Orogenic Gold Deposits of the Ahafo South Camp, Sefwi Granite-Greenstone Belt, Ghana

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The application of hyperspectral analysis provides the ability to address inconsistent recognition of alteration minerals captured by traditional logging methods. Routine hyperspectral analysis of drill core provides semi-quantitative mineralogical data which allows for objective identification and classification of alteration assemblages and domains. The composition and distribution of alteration assemblages can be further refined by pairing the hyperspectral results with rock hardness measurements collected via a handheld rebound device. Within the Ahafo South camp, hanging wall alteration zonation developed within granodiorite and diorite host rocks, displays systematic mineralogical variation as a function of distance to known fluid pathways.

Distal alteration is characterized by the conversion of amphibole to Mg-rich chlorite. With increasing proximity to the dominant fluid pathway, primary plagioclase and secondary chlorite are replaced by calcite and phengite. Continuing to approach the primary fluid conduit, Fe-carbonate, and ammoniated mica form and phengite transitions to a muscovitic composition. Additionally, there is a shift in the chlorite 2250 nm and 2350 nm absorption features to longer wavelengths indicating more Fe-rich compositions before chlorite is ultimately altered to muscovite and dolomite. Proximal to fluid conduits within mineralized zones, the alteration assemblage consists of pervasive albite+dolomite+pyrite+gold±quartz with Fe-rich chlorite developed locally in mafic host rocks. This assemblage is characterized by complete destruction of primary textures and increased rock hardness. Though albite and quartz are not hyperspectrally active within the shortwave infrared range, their presence has been confirmed by XRD analysis and petrography and correlated to mineral proxy parameters generated from the hyperspectral data. Establishing a relationship between relative rock hardness and the semi-quantitative mineralogy generated from hyperspectral analysis provides a link to create consistent, multi-parameter, 3D domain models that can influence exploration targeting as well as mining and process related functions.

Critical Minerals: An opportunity to be considered in Chile

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The term "critical minerals" is used to refer to minerals of great economic importance to a particular industry, country or geographical area and are at risk of supply shortages. These minerals are not only "critical" for key industry sectors and future applications, but also for the sustainable functioning of the global economy and its aspirations to become carbon neutral by 2050.

In 2014, the European Union did a study that identified some 46 metals and minerals that it deemed critical to its industry. Taking as an example the case of the EU, I proceeded to review which metals or minerals on the list of its Critical Minerals we have in Chile.

It turned out that our country is a producer of 20 of them and additionally has in its deposits another 6, which could also be produced. It is obvious that, given our recognized capacity as minerals producers on a global scale, the issue of Critical Minerals should be studied, evaluated and considered to be taken advantage of by our country.

With a good knowledge of critical minerals, many old mines now paralyzed and our abundant waste from mining: tailings, clearings and slags should also be evaluated. Many of which have various metals and minerals from this special group that we could now take advantage of.

Accordingly, we could carry out the much mentioned, but little realized "circular economy". The opportunity is identified. Now we have to act to take advantage of it.

The formation of the Exótica deposit at Chuquicamata, Chile

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Detailed mineralogical and textural studies, combined with sequential X-ray diffraction and geochemical modeling helped to solve the “copper pitch/wad” enigma in the Exótica deposit located downstream of the Chuquicamata porphyry copper deposit, Chile. Copper pitch and copper wad are essentially chrysocolla with co-precipitated Mn-oxides, mainly birnessite, as well as pseudo-amorphous Mn oxide/oxyhydroxides. Linking the mineralogical, geochemical, and textural evidence with the geological, tectonic, and climatic evolution of the Chuquicamata-Calama area, a four-step model for the evolution of the Exótica deposit is presented:

1) Formation of a mature supergene enrichment profile at Chuquicamata (~25 Ma to ~15 Ma) during an erosion dominated regime (∼900 m of erosion). The resulting acidic (pH ∼2-4) Cu-Mn-Si dominated rock drainage (ARD) was flowing through the Exótica valley towards the Calama Basin, resulting in a strongly kaolinized and chrysocolla/copper wad impregnated bedrock of the Exótica deposit.

2) Deposition of the Fortuna gravels in the Exótica valley (starting ∼19 Ma) intercepted the Cu-Mn-Si dominated ARD, triggering the main chrysocolla, copper pitch/wad mineralization as syn-sedimentary mineralization by chiefly surficial-flow in strongly altered gravels.

3) Tectonic freezing and onset of hyper-aridity (∼15-11 Ma) exposed the enriched chalcocite blanket of Chuquicamata to oxidation, resulting in an acidic (pH ~2-4) and Cu-Si-dominated solutions with less Mn. These solutions percolated in a slightly more reducing groundwater flow path mineralizing the relatively unaltered gravels with pure chrysocolla.

4) Ingression of confined chloride-rich groundwater in the upper oxidation zone of Chuquicamata, most likely between 6 and 3 Ma, is responsible for the atacamite/brochantite mineralization (pH ~5.5-7) of mainly unaltered gravels in the northern and central part of the Exótica deposit.

High-Resolution 3D Geoscientific Information for Material Control and Short-Term Decision Making in Open Pit Mining Operations

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Open-pit mine geologists and short-term planners often have no choice but to use low spatial resolution information for short term decision making. Even well sampled attributes such as metal grade are a composite of a bench and thus limited to 2D views of the material to be mined. Other key attributes such as ore/waste boundaries, blastability, comminution hardness, waste rock types are more generalised to lithology/alteration types or via poorly sampled proxies. Maximising value and reducing the risk of unwanted outcomes is problematic with current practices and very difficult to take advantage of emerging technology solutions. The bench is the last time the material is in situ and can inform the short term mine plan, i.e., decisions regarding blasting, screening, stockpiling among others, before these materials are subject to processing. Improved knowledge at bench scale can inform and influence a large range of downstream decisions and assist improving operational performance and margins.

Imdex has developed the BlastDog as a key tool to provide high spatial resolution material physical property measurements at the time of blast hole drilling across a range of commodities. This data through analytics can provide information for decision making to a range of personnel such as geology, scheduling, mining engineering, geotechnical, blasting, processing, and metallurgy. Examples of the information from BlastDog will be shown.

Applied Mineralogy techniques used to verify the normative mineralogy modeling based on the geochemical data: The strength and limitations of the common mineralogy techniques

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While the geochemical data provide a direct quantitative characteristic of the elemental distribution in an ore deposit, a qualitative outlook can be concluded using mineralogy data. One can calculate a semi quantitative/normative mineralogy based on the chemical data (such as CIPW method), however, dependent on the rock type and the minerals of interest, not always the prerequisite of such approaches cannot be held and verification by a conventional mineralogical analysis, such as XRD or Automated SEMs are still required. Once a thorough understating of the major and trace mineralogy of the deposit has been achieved by using common applied mineralogy techniques, the mineralogical variation through the deposit can be modelled using the geochemical data. Therefore, geometallurgy tests, such as

QEMSCAN or XRD, are recommended to complement the normative calculation during early stages of the exploration.

With availability of a wide range of mineralogy analytical techniques, such as handheld field equipment, Hyperspectral Analysis, or Automated SEMs, it is important to understand the functionality and strength of the method before applying it as reference for the normative mineralogy modeling.

Here we review and compare the mineralogical data, generated using XRD, QEMSCAN, Petrography Study and LA-ICPMS during early stages of an exploration project, and compare the discrepancies of the results among the methods with their geometallurgical implications.

Although the expectation was to achieve a close result between QEMSCAN and XRD, the methods retuned a high discrepancy due to the nature of the samples. The petrography test was performed to confirm the sources of the discrepancy between QEMSCAN and XRD, while the LA-ICPMS was used to detect the source of the trace elements that could not be concluded by QEMSCAN. We explore the source of technical errors and uncertainties by comparing the results from the mineralogical tests and the chemical assay.

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Geometallurgy of Cobaltiferous Copper Ores of the Chilean Iron Belt

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Chile has a long history of copper mining, both in copper sulfides and copper oxides. Despite of the relative importance of other elements, such as molybdenum, gold, silver, and lithium, it is fair to say that in Chile copper is what drives the mining industry. However, cobalt could be a game changer in the future. Copper grades are consistently decreasing, putting profit margins at risk. In parallel, electromobility is driving the demand for cobalt at a global scale, as it is a necessary component of the batteries for electric vehicles.

Primary copper-cobalt ore deposits are found along the western edge of the Chilean Iron Belt of the coastal cordillera of the Atacama and Coquimbo regions, vein deposits mainly hosted within the Atacama Fault System. These deposits present an ore mineralogy consisting mainly of chalcopyrite and cobaltite (a cobalt-arsenic sulfide). In the oxide zones these deposits present copper oxidized minerals and erythrite, a cobalt arsenate. Within this same Iron Belt, iron and/or copper deposits have potential for cobalt-bearing sulfide minerals, largely and most interestingly in pyrite. The main deposit types in which to evaluate cobalt as a potential by-product are the IOCG, followed by the IOA, and to a much lesser extent, the porphyry copper.

The cobalt grades in the Chilean deposits are relatively low and its potential to add value can be significant, albeit limited to its recovery as by-product, which is currently being evaluated in the development stage of several copper projects in the region. For cobalt to have economic value, the metallurgical process design must be well aligned with the geological features of cobalt, so that the overall process to recover copper does not jeopardize the potential for cobalt recovery.

Key words: Cobalt; Geometallurgy; Chilean Iron Belt

REE Deposits in South-Central Chile: An exploration overview of Ion- Adsorption Deposits

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Introduction: The Rare Earth Elements (REE) are economically important for a variety of high-technology applications, and Heavy/Medium REE mostly are used for permanent magnets, essential for electronics, electric vehicles, and renewable energy. Most of today´s world’s Heavy/Medium REE production is from south of China, specially mined from unconventional deposits formed in weathered granitic profile as the result of humid tropical to temperate climate conditions. These deposits are known as Ion-Adsorption Deposit (IAD) or Regolith-hosted, formed by chemical weathering decomposition and leaching of granitoid rocks and REE primary minerals, and subsequent accumulation of REE cations mainly by adsorption on clay minerals during the migration of solutions (Sanematsu and Watanabe, 2016; Li et al., 2020; Bustos et al., 2022).

IAD are the main sources of Heavy REE and only a few deposits were discovery the last decades outside China. Regardless the economic importance, little is known about IAD formation and their genetic process, including controls on REEs ionic mobilization and concentration.

REE Deposits in South-Central Chile: In the Coastal Cordillera of South-Central Chile, Paleozoic granitoid rocks were widely affected by template humid climatic conditions, which produced the development of an extensive and deeply weathered crust. These strongly altered profiles (saprolites) generate abundant clay minerals, which locally can host REE-rich horizons.

The in situ weathered granite profile generally include three main horizons which correspond to: A) an upper part composed of organic soil depleted in REE contents; B) a middle portion of strongly weathered crust that may or not contain a REE-rich clay horizon; C) a bottom unit composed of a weak-weathered rock with low REE values. Finally, below these horizons is the parent intrusive fresh rock. However, saprolites can be characterized by vertical distribution of clay mineral assemblages and particle size distribution.

REE-rich clay horizon formation and location in the weathered profile are function of lithology and REE mineral-types, climatic variations, geochemical conditions, groundwater flow, landform, and geomorphic controls. Understanding REEs ionic mobilization and stability factors has direct implications for conceptual IAD exploration.

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Multi-scale, multi-modal and multi-dimensional workflow for the rapid characterization of exploration drill cores – a Au-Co case study from Finland

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Exploration geologists are always faced with the challenge of how to bridge the scales of observation found in nature, especially going from field-scale observations (3D-4D) down to laboratory-based imaging and analysis (3D-2D). Using concepts and practices based on allied areas (for example, oil and gas reservoir characterisation and material science), a new workflow is proposed that takes full advantage of the range of geo-analytical techniques that are available today (including optical, e-beam, x-ray beam, and laser beam). By using all these complimentary techniques, it is possible to upscale and downscale, as well as maximise discovery, and in the process analyse features of special interest to help with the understanding of the geological processes involved in deposit formation and, moreover, the potential downstream mineral processing strategies required. This includes mapping the 3D distribution of elements and minerals of commercial importance, as well as 2D surface analysis to quantify micro-chemical mineral compositions and other textural features, such as mineral associations, grain sizes and grain shapes, as well as micro-structural information. A special feature of this workflow is to be able to map samples that are significantly larger in area than that typically covered by a standard petrographic or e-beam probe thin sections, using scanning micro-XRF technology. This case study is based on samples from the Au-Co project from the Mawson project in northern Finland. Work is on-going, but early results suggest there is added value of such an approach, with a much-improved understanding of the exploration and deposit potential.

Characterizing the geochemical and geophysical properties of an orebody to select the optimal sensor for sensor-based sorting

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In recent years there has been significant growth in the application of sensor-based sorting techniques employed by mining companies to help remove waste rock or to upgrade ore prior to downstream metallurgical processing. There are various sensor technologies available from sorter manufactures including but not limited to X-ray transmission (XRT), laser scattering, colour, mid-IR and so forth. Assessing the geochemical and geophysical properties of the ore to assist in characterizing the ore is essential to understanding how the sensors interact with minerals and to the selection of the best sensor for sorting purpose.

XRT sorters are a popular choice for mineral processing plants since they can sort a wide variety of minerals. The current test procedures used to evaluate the amenability of the ore to XRT sorting is to pass the particles through the sorter and obtain the greyscale images showing atomic density differences in the mineralogy. This test provides information on the mineralogical heterogeneity between ore particles for XRT separation, but it does not provide an understanding of the actual mineralogical composition of the ore, liberation information or the response of other minerals. The Saskatchewan Research Council (SRC) has developed a series of tests that combines the use of geochemical data, X-ray micro–Computer Tomography (CT) and QEMScan to obtain information about amenability of ore to sorting and to obtain valuable information that can streamline metallurgical test work programs. These tests also provide information relating to particle thickness and associated X-ray attenuation coefficients, desired mineral presence and mineralogical information relating to associated minerals and clays to assist with developing sorting algorithms

A recent investigation of four sorting technologies (XRT, laser scattering, colour and mid infrared) for preconcentrating a gold ore determined that all four sorting technologies were able to preconcentrate the ore to varying degrees with mid infrared, colour and laser scattering providing viable results.

Combining the CT, QEMScan and geochemical data to characterize the ore before processing the ore through a sorter can address the many limitations of the current testing method and establish better outcomes for sensor-based sorting. The application of sensor-based sorting methods to preconcentrate and upgrade orebodies prior to processing will be increasingly necessary to reduce mining costs and improve environmental impacts.

Mapping porphyry alteration more specifically: integrating geochemistry and hyperspectral imaging data at the Caspiche Porphyry, Chile

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Caspiche is a gold-copper porphyry located in the Maricunga Belt of northern Chile. The deposit is characterized by a central gold-copper zone and is hosted in diorite to quartz diorite porphyry stocks. The alteration system is documented extensively by Sillitoe et al. (2013), which clearly details the alteration styles (i.e., potassic, potassic-calcic, chlorite-sericite, propylitic, and advanced argillic) and major reaction fronts (i.e., base of leach cap and sulfate).

Analysis of recently collected hyperspectral imaging (HSI) allows us to expand upon the previous work, particularly with the more cryptic alteration minerals not previously identified. Importantly, the HSI data also allows us to examine the alteration on a large scale. To date there are 42 minerals mapped at the project, in addition to 11 compositional (chemistry and crystallinity) parameters. Mineralogical maps (images with ~200,000 pixels of mineralogical information per meter) and semi-quantitative mineralogy (25cm intervals) is available on over 60,000 meters of diamond drillcore.

While this amount of information seems daunting, there are simple ways to investigate HSI data to immediately add value to a project. This starts with striking “sericite” from the mineral list and looking at the distribution, relative abundances, and the chemistries of white mica, illite and montmorillonite.

Distinctive to Caspiche is that the mafic minerals and calc-sodic minerals are related to the highest gold and copper grades, therefore tracking these mineral assemblages and chemistry changes (e.g., in chlorite and amphiboles) is important. This study builds upon field observations such as these, focusing on making the geologic language more specific through application of HSI data.

Reference

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Meteorite classification using QEMSCAN: First results for ordinary chondrites from the Atacama Desert

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After the discovery of high meteorite density per km^2 in some surfaces of the Atacama Desert in 2016, the number of foreign expeditions, scientific and from private collectors, increased dramatically, with a subsequent loss of these meteorites from the country. One action that could contribute to keep at least the type specimen in the national museums, is to classify the new recoveries in Chile. The problem of that is the scarcity of microprobes in Chile that could analyze Fa and Fs in olivines and orthopyroxenes, respectively, for the most abundant type of meteorites, the ordinary chondrites (OCs).

A solution has been attempted using Qemscan® (Quantitative Evaluation of Minerals by Scanning Electron Microscopy), a great technique that combines an image analysis system that measures mineralogical variability based on chemistry at micrometric scale. The technique generates a particle map with semi-quantitative non-volatile element abundances from which the modal abundance and occurrence of mineral phases are estimated. The main challenge of Qemscan to have similar results to the microprobe analysis relies in the appropriate definition of the Species Identification Protocol (SIP) list, that has been built by the user before analysis, trying to give the best approach of the mineralogical composition of each phase expected for the meteorites, in this case being the OCs. In this work, we present the classifications obtained for different samples of OCs found in Atacama Desert, as well as the results of the Qemscan study of five OCs classified before by microprobe, in order to calibrate and measure the deviation seen in the Fa and Fs, using them as a calibration source for Qemscan.

This preliminary study used two Qemscan equipments: a ZEISS EVO 50 Scanning Electron Microscope (SEM) combined with Bruker Series 4 energy dispersive spectrometer (EDS) detectors at Maini-UCN facility in Antofagasta, and a Tescan Vega LSH (SEM) combined with 4 Bruker XFlash 14010 Silicon Drift Detectors at GEA-UDEC, in Concepción. They were used to get mineralogical maps of 16 meteorites, using polished sections, studied by the authors. Five samples have already been classified by microprobe data (Paposo LL6; San Juan 086 L6 breccia; Pampa (a) L6; Los Vientos 357 H6; Taltal 001 H3, classification taken from https://www.lpi.usra.edu/meteor/metbull.php).

The sixteen OCs analyzed so far with Qemscan, have provide semi-quantitative chemical compositions for most meteorite phases. From the modal abundances of the minerals identified (olivine, pyroxenes, plagioclase, Fe-Ni, troilite, chromite, apatite, zircon, carbonates and others), - each of them represented with a false colour on the map -, it was possible to obtain the chemical values of Fe^0, total Fe and Si calculated from the % of these elements in the modal mineralogy, that enable to calculate the ratios Fe^0/Fe and Fe/SiO_2, allowing the classification of chemical groups (H, L or LL OCs). The samples previously analyzed by microprobe gave similar results for the chemical group classification using the data obtained by Qemscan, as well as the quantification of the different components, including the general weathering species (Fe oxi-hydroxides + alteration minerals in silicates). Once the comparison was successful, other 11 new OCs were analyzed using the same methodology. The persistent problems observed are the definition of fine grain phases, as the mesostasis inside chondrules or in glassy components, as well as the alteration of silicates. The oxi-hydroxides are also under-quantified, as the presence of Fe and Ni in the new formed minerals are interpreted as kamacite.

These problems are easy to correct if a complete petrographical study is done previous to the Qemscan analyses. A better constrain in the parameters of these more problematic phases can be improved with more analyses of different type of stony meteorites, that will allow the recognition and quantification of every mineral phase in this kind of meteorites, when the SIP list for meteorites is well constrained for each mineral phase. In this way, next steps include the analyses of carbonaceous and enstatite chondrites, as well as all sorts of achondrites.

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The Role of Geochemistry and Geometallurgy in Sustainable Resource Development

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The effects of accelerated human-induced global warming are driving up the desire for a low-carbon energy transition with concomitant growth in metal demand. At the same time, the minerals sector is under ever greater scrutiny to deliver resources in the most responsible and least impactful way possible. This requires the industry to improve on its track record throughout the entire mining value chain by optimizing its systems and processes holistically with new approaches. Historically, the fields of mineral exploration, mining, and processing were generally understood by geologists and metallurgists and knowledge would be shared among small teams involved in resource development and production. More recently, science and engineering have become more specialized and diversified, leading to siloing in organizations and dissociation of exploration geosciences from mining operations and environmental impacts. This knowledge gap has grown to the point that a bridging discipline known as geometallurgy is now required to reconnect the disparate functions through designated teams of specialists. Mineral processing is primarily affected by mineralogy, which dictates grade, hardness, material handling, metal deportment, and recovery parameters. Likewise, chemistry and mineralogy control the metal-leaching and acid-drainage potentials of waste rock and tailings. However, detailed mineralogical data are usually only acquired in small volumes of metallurgical and environmental testwork, or in the early stages of exploration. High quality multi-element geochemical data are more commonly available for thousands of drill-hole intervals, providing the closest approximation of an orebody’s mineral composition. If understood and analyzed well, such geochemical data can play a critical role in material characterization for all downstream processes, including mining, milling, metallurgy, waste and tailings management, and closure planning.

Oral Presentations

Technical Session 5

Environmental geochemistry: closing the gap for sustainable mining and development / Mine Tailing Revalorization (Unesco-IGCP682)

Environmental geochemistry of seven fluvial systems in Chile: Lluta, Copiapó, Huasco, Limarí, Rapel, Valdivia and Aysén river basins

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In this study, the environtmental conditions of seven relevant fluvial systems in Chile, namely the Lluta, Copiapó, Huasco, Limarí, Rapel, Valdivia and Aysén river basins, are assessed. For this purpose, the contamination, and ecological risks of eight metals and metalloids (As, Hg, Cd, Cr, Ni, Pb, Zn and Cu) was evaluated by using four geochemical indexes: 1) the index of geo-accumulation (Igeo), 2) the enrichment factor (EF), 3) the modified contamination degree (mCD) and 4) the potential ecological risk index (RI). The analyzed database was generated by Sernageomin, in the context of the Program of Geochemistry of the National Geology Plan. The results indicate that, of all the evaluated fluvial systems, the Valdivia River basin is the one with the lowest rates of contamination and ecological risk. This result contrasts with what was observed in the other 6 river basins. In all of them, at least an important section of the fluvial system, presents high degrees of contamination and ecological risk. In particular, in the Huasco and Limarí river basins, the most complex environmental situation is related to natural factors. In both cases the origin of the geochemical anomaly coincides with the existence of a mineralized area in the headwaters of the catchment (La Coipita area in the Limarí basin and Pascua Lama area in the Huasco Basin). In contrast, the high values of contamination and ecological risk observed in the Lluta, Copiapó, Rapel and Aysén river basins, are highly likely associated with an anthropic factor (mining activities). This conditions, including those of the Huasco and Limarí basins, entails a risk for the population and the biota of these fluvial basins. Therefore, it is necessary to maintain permanent environmental monitoring that includes the evaluation of the content of metals in the exposed animal and human population.

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Electrokinetic *in situ* leaching of copper

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Electrokinetic in-situ leaching (EK-ISL) of copper is a potential mining process that recovers copper from orebodies without physical excavation, considerably lowering the mining operation's environmental imprint. Its proof of concept has so far been established at small-scale [1]. However, the feasibility at the industrial scale is heavily contingent on having a thorough knowledge of the in-situ geochemical processes that occur during the leaching. Subsequently, the appearance of secondary layers has been found to have a significant influence on the efficiency of copper sulphide leaching. So far, the specifics of their development have only been researched in ex-situ circumstances with ground or synthetic samples. These secondary products are typically attributed to hinder recoveries in hydrometallurgical systems.

In this study, we investigate the mechanism of Electrokinetic leaching of intact Cu ore samples with ferric sulphate and ferric chloride media. The main focus is on surface-controlled processes, including a comprehensive description of the mineral surface as it evolves throughout the reaction. A wide range of characterisation techniques was employed to identify the solid phases, including quantitative X-ray diffraction (QXRD), scanning electron microscopy (SEM), and Raman microspectroscopy. The laboratory electromigration tests quantify total reaction progress and extraction efficiency. In addition, a tracer test was performed to characterise the physical transport properties of the ore material.

Results showed almost 95% recovery using ferric chloride and around 40% with ferric sulphate. All dissolution curves depict a parabolic shape, suggesting a decreasing rate due to diffusion-limited transport of ions across precipitates around the copper minerals. The neo-formed phases slowed copper recovery, though did not entirely stop the leaching process. Finally, a combination of SEM and deconvoluted Raman spectra showed the successive formation of longer-chain polysulphides, indicating the sustained dissolution of polysulphides, under the in-situ geochemical conditions, exposes new mineral surfaces to oxidation. Importantly, this allows for secondary phase re-solubilisation and potentially improves copper recovery.

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Reactive transport modelling of a multistage copper leaching experiment: Implications for in situ recovery

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A significant fraction of base metal deposits is currently deemed uneconomic to mining by conventional methods due to the increasing depth and declining grades of new ore discoveries. In situ recovery (ISR) has been proposed as a promising alternative to conventional mining. If viable, ISR would completely eliminate the hauling and grinding of large volumes of rock and provide a more environmentally friendly mining approach. Nevertheless, to date ISR applications have, with few exemptions, largely been limited to uranium mining.

We use column experiments and numerical modelling to investigate the coupled transport and leaching phenomena that will determine the potential copper recovery at a prospective ISR site in South Australia. Four experimental columns were operated using a multistage approach comprising leaching with (1) the native acidic groundwater from the study site (2) a 0.1 M H_2SO_4 amended lixiviant, (3) a 0.1 M H_2SO_4 and 0.1 M Fe^{3+} amended lixiviant and finally (4) a 0.1 M H_2SO_4 and 0.5 M Fe^{3+} amended lixiviant. A pre-experimental mineralogical characterisation of the solid samples was conducted using QEMSCAN and QXRD. Elemental compositions of the solution and solid phase samples were obtained by ICP-OES.

Experimental results were integrated and analysed through reactive transport modelling. Solute transport was simulated using a dual domain mass transfer (DDMT) approach to accommodate the occurrence of preferential flow processes. A reaction network describing the key reactions involved in the leaching process was developed, and multiple conceptual model variants were evaluated against the collected solution and solid phase data.

The results demonstrate that the recovery in the experimental columns was primarily controlled by the mineralogical composition of the ore. The rate of recovery was fastest in the first two leaching stages, during which the more soluble copper minerals (e.g., chalcanthite) and copper carbonates (e.g., malachite) were dissolved. Declining rates during leaching stages 3 and 4 prevented a more complete recovery at the prevailing ambient temperature (25 °C). The observed liberation of dications during the last two stages was explained by a co-dissolution with pyrite. Finally, predictive model simulations were performed to illustrate and assess the viability of copper recovery at the field-scale.

Column leaching of oil sands froth treatment tailings: Comparison of capping scenarios

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The oil sands in northern Alberta represent the third largest reserve of crude oil in the world. Froth treatment tailings (FTT) are a type of waste produced from the bitumen extraction process from these deposits. FTT represents a small proportion of oil sands tailings yet presents unique challenges. At mine closure, tailings will need to be reclaimed and capped by soil to allow reclamation of the landscape. Unlike other oil sands tailings streams, FTT often contains higher proportions of the mineral pyrite which has the potential to oxidize to produce acidic rock drainage. The objective of this research is to study the impact of using different capping materials overlying tailings on the potential for acid generation. This is being achieved by using six columns (height: 1.8 m, diameter 0.15 m) with three different configurations of tailings sand, clean quartz sand and peat. Two of the columns contain FTT overlain by peat, two columns have quartz sand overlain by peat and two columns have FTT overlain by quartz sand. The hydraulic head in the columns was maintained at 10 cm below the soil surface throughout the experiment.

On a weekly basis 800 mL of water was added to the top of the columns and 800 mL was extracted from the base. Samples were collected for monitoring of routine parameters (*e.g.,* temperature, electrical conductivity, dissolved oxygen, solution pH and oxidation-reduction potential), major ions, trace metals, benzene, toluene, ethylbenzene, xylene (BTEX), polycyclic aromatic hydrocarbons (PAH), carbon isotopes, and microbial community composition. Results to date show an initial flushing of dissolved ions from tailings and peat and development of reducing conditions. After one year, the solution pH of one of the columns containing tailings capped with quartz sand started to decrease and a corresponding increase in dissolved iron and sulphate was also observed, while other columns' pH remained circumneutral. Results obtained to date will be presented.

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Improving and diversifying mine tailing revalorization through detailed mineralogical and geochemical analysis at a current tailings recovery plant (Minera Valle Central, Chile)

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The existence of huge volumes of tailing deposits in Chile has generated interest in reprocessing with the aim of extracting metals of economic/environmental interest. This work seeks to evaluate in an applied way the possibility of incorporating and recovering other elements / minerals of interest to the usual process.

The concentrations of metals and minerals of interest throughout the Minera Valle Central (MVC) sulphide flotation processing plant indicate significant increases in their concentrations at different stages of the processing flow. Cobalt, which has been associated with pyrite as the main carrier mineral, is particularly interesting. Likewise, pyrite is naturally concentrated in the plant process, particularly in the cleaning sequence, where it is separated from the copper concentrate, where it is returned to the tailings deposit. During the cleanup process, cobalt concentrations rise close to an order of magnitude (~160 ppm) from the original concentration (~20 ppm) in the tailing deposit. Such behavior makes it possible to establish methodologies to retain pyrite concentrates and generate an economic recovery of cobalt.

The results of our studies demonstrate that even in a standard plant design, there are opportunities to concentrate and extract elements / minerals of interest with minimal intervention. Studies of the mineral / geochemical behavior of plant flows suggest opportunities for by-product recovery.

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Oral Presentations

Technical Session 6

Water and hydrogeochemistry: Challenges in exploration, mining, and sustainable development

Geothermal fluids and lithium deposits in the salt flats: An assessment of their association at Laguna Verde, Atacama Region, Chile

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The association between geothermal fluids and lithium (Li)-rich brines in salt flats is often speculative due to the absence of an active present-day geothermal system to associate it with such deposits. However, the presence of an active geothermal system with surface manifestations and outcrops of the potential Li source rocks within a salt flat in the Chilean Andes with a hypersaline lake – Laguna Verde (LV) – within a closed basin delimited by a series of volcanoes a together constitute a natural laboratory to evaluate this association. In the LV area, andesitic-dacitic rocks predominate the lithology, with the limited occurrence of rhyolitic rocks (sequences with ignimbrites and glass-rich ash) reported in the boreholes drilled for mineral exploration (gold and copper). Li is leached by geothermal fluids from the aforesaid potential sources, and this process is active intermittently since Miocene time. The outflow zone of the LV geothermal system is marked by more than 20 hot springs with temperatures up to 47°C near the southern margin of the lake; while the fumarolic field in the Nevado Ojos del Salado volcano, 25 km SSW of LV, represents the upflow zone. The considerable distance between upflow and outflow zones (i.e., the geothermal system's extension) is the most plausible reason for re-equilibration(s) between the chemical species during the long-distance travel of thermal water. This causes underestimation of reservoir temperature (85 and 90°C using Na-K-Mg and silica geothermometers, respectively). Li concentrations vary between 2.76 to 4.46 mg/L and 0.59 to 0.76 mg/L in thermal and Peñas Blancas river water. Peñas Blancas River feeds LV after passing through the volcanic environment (Li-rich rocks), thus enriching water in Li. However, Li contribution of over six times the non-thermal water envisages the importance of the thermal waters in Li release and transport from the source rock to its eventual concentration in LV. The dynamic environment at LV would have formed brine of different Li concentrations interspersed within the basin fills clastic sediments. Moreover, geothermal fluids-induced circulation of the brines might have developed a heterogeneous Li vertical distribution, with the economic brines occurring well below the lower Li concentration aquifers.

Stream Sediment Sample Catchment Analysis using Open-Source Tools

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Stream sediment geochemistry is a common component of mineral exploration campaigns in more rugged regions where regional soil or lake sediment sampling is not feasible. The chemistry of the stream sediment sample is assumed to be representative of the bulk geology of the catchment area for a given sample point and therefore sample placement is critical for efficient and robust survey design. There has been considerable work investigating stream sediment geochemistry datasets by integrating the sample with its 2D sample catchment surface area and applying various levelling strategies to account for variation in catchment geology, catchment size related chemical dilution, etc. The catchment-based workflow requires the delineation of high-quality sample catchment polygons and for most previous work this processing was completed with proprietary software such as MapInfo-Discover or ArcGIS. An evaluation of available free and open-source software (FOSS) tools has led to the development of a workflow capable of generating sample catchment polygons quickly and effectively at no cost using QGIS Desktop GIS software and the PCRaster environmental modelling package developed by Utrecht University in The Netherlands (Karssenberg et al. 2010). This workflow will be documented and described with an example dataset to illustrate the process and data products created.

Reference

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Hydrogeochemistry of mine tailings from a carbonatite-hosted Nb-REE deposit, Oka, Québec, Canada

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Environmental impacts associated with the mining of carbonatite deposits are an emerging concern due to the demand for critical metals. This study investigates the chemistry of tailings seepage at the former Saint Lawrence Columbium mine near Oka, Québec, Canada, which produced pyrochlore concentrate and ferroniobium from a carbonatite-hosted Nb-REE deposit. Its objectives are to characterize the mineralogy of the tailings and their pore water and effluent chemistries. Geochemical mass balance modeling, constrained by aqueous speciation modeling and mineralogy, is then used to identify reactions controlling the chemical evolution of pore water along its flow path through the tailings impoundment. The tailings are composed mainly of REE-enriched calcite (82 wt. %), biotite (12 wt. %) and fluorapatite (4 wt. %). Minor minerals include chlorite, pyrite, sphalerite, molybdenite and unrecovered pyrochlore. Secondary minerals include gypsum, barite and strontianite. Within the unsaturated zone, pore water chemistry is controlled by sulfide oxidation and calcite dissolution with acid neutralization. With increasing depth below the water table, pore water composition reflects gypsum dissolution followed by sulfate reduction and FeS precipitation driven by the oxidation of organic carbon in the tailings. Concomitantly, incongruent dissolution of biotite and chlorite releases K, Mg, Fe, Mn, Ba and F, forming kaolinite and Ca-smectite. Cation exchange reactions further remove Ca from solution, increasing concentrations of Na and K. Fluoride concentrations reach 23 mg/L and 8 mg/L in tailings pore water and effluent, respectively. At a pH of 8.3, Mo is highly mobile and reaches an average concentration of 83 µg/L in tailings effluent. Although U also forms mobile complexes, concentrations do not exceed 16 µg/L due to the low solubility of its pyrochlore host. Adsorption and the low solubility of pyrochlore limit concentrations of Nb to less than 49 µg/L. Cerium, from calcite dissolution, is strongly adsorbed although it reaches concentrations (unfiltered) in excess of 1 mg/L and 100 µg/L in pore water and effluent, respectively. Mine tailings from carbonatite deposits are enriched in a variety of incompatible elements with mineral hosts of varying reactivity. Some of these elements, such as F and Mo, may represent contaminants of concern because of their mobility in alkaline tailings waters.

Geochemical, mineralogical characterization and geostatistical modeling of an IOCG tailings deposit: implications for environmental safety

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In the mining industry deposits of tailings represent large volumes of the mining wastes, reflecting the mineralogy and chemistry of the ore deposit type of origin. In this paper, we report the results of a mineralogical and geochemical characterization study and geostatistical modelling of an Iron Oxide Copper Gold deposit with neutral pH, in an arid climate. Twenty-eight boreholes allowed recovery of 755 samples for analysis. Modelling by means of co-kriging spatial interpolation allowed determination of the distribution of concentrations for elements of interest in the deposit. Low water flow and near neutral-pH paste restrict the mobility of the chemical elements, limiting the development of an oxidation front and inhibiting the appearance of a secondary mineral enrichment zone and the precipitation of secondary efflorescent salts on the tailings surface. Our observations determine that the composition of the gangue material, and to a lesser extent the effect of the tailings gravitational deposition and the geometry of the deposit, control the geochemical and mineralogical associations and distributions present in this deposit of tailings. The observed low mobility along the tailings profile of some potential pollutants (e.g., As, Mn, Cr and Ni) allows to anticipate a low groundwater pollution risk if the current environmental conditions remain. Additionally, the depositional history of the tailings had a great influence on the vertical and horizontal distribution of pyrite. However, the grades of elements of economic interest such as Fe, Cu and Co are uniformly distributed, which would facilitate the application of tailings reprocessing technologies.

Geochemical signatures of porphyry deposits in ground and stream waters: erosion, enrichment, and alteration

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The dispersion of metals in ground and surface waters from hydrothermal mineral deposits has been shown to be an effective vector in mineral exploration and where water can be sampled, a tool to explore where deposits are deeply emplaced or covered by post-mineral deposits. The atypical geochemical signatures (Mo, Se, Re, As, Cu) of porphyry systems are commonly reflected in water chemistry around mineral occurrences. However, the successful application of hydrogeochemistry in mineral exploration requires an understanding of the geological and hydrological controls on metal dispersion in aqueous environments. Such variation can be introduced as a function of (but not limited to): (i) aqueous chemistry; (ii) deposit weathering and extent of secondary enrichment; (iii) erosion; (iv) hydrology; as well as (v) development and extent of alteration. Understanding this variation is key to interpreting hydrogeochemical datasets in different settings and establishing background thresholds. A multifaceted approach to hydrogeochemical mineral exploration, coupling trace elements and stable isotope geochemistry is the most effective vectoring approach. This talk presents recent work undertaken at the Casino porphyry Cu-Au-Mo deposit in the Dawson Range, Canada as well as comparisons from studies globally, to provide a range of prospective hydrogeochemical signatures associated with expected geological scenarios. This talk aims to highlight effective methodologies for exploration hydrogeochemistry.

The Geochemical Anomalies of the Turbio River, Coquimbo Region, North Central Chile, and its Environmental and Economic Bearings

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In the Toro river (20° 46'S / 69° 59'W; 4,100 m a.s.l.) lays the El Indio (Au-Cu-As) deposit. An extensive hydrothermal alteration zone spreads along the river. The confluence of Toro and La Laguna rivers forms the Turbio river, that downstream receives the Incaguaz river. The confluence of Turbio and Claro is the onset of the Elqui river. La Laguna, as well as the Incaguaz and Claro rivers, drain the southern part of the basin. Their waters have low metallic contents. On the contrary, exceedingly high Cu and As contents in the fine sedimentary fraction are in the Toro, Turbio and Elqui rivers, with over 0.1 wt% Cu, 300 ppm Zn and 100 ppm As (averages). These anomalies boosted several complementary studies, as one where a carbonaceous, gypsum rich bed terrace level in the upper curse of the Turbio river, containing 3,500 ppm Zn, 700 ppm Cu and 750 ppm As was observed. This layer, dated at 9,640 years, was interpreted as the bottom of a short-lived lake, receiving acid rock drainage (ARD) from the El Indio zone.

El Indio mining works began in 1975 by St. Joe Mining. Five years before, moderate Cu, As and Mo anomalies in the area were described, when only small scale mining was active. A study based on DGA (Chilean Water Agency) monitoring data of the Turbio river, concluded that between 1975 and 1995 the Cu water content increased from 0.02 to 2 mg/L and that of As from 0.05 to 0.33 mg/L, revealing an overprinting of the mining activities over the natural ARD prone conditions. After the closure of the mining operations (ca. 2002), ARD has remained active. A comparison of the DGA data for the Toro river in 1996-2006 and 2007-2016 revealed a reduction of the Cu content from 17 to 10.5 mg/L, but an increase of SO_4 (943 to 1,102 mg/L) and a persistence of As at 0.5 mg/L.

This work analyzes factors involved in the magnitude of the Turbio river anomalies and present an experimental assessment of the stability of potentially toxic element contained in the fine sediments. The new sampling and analysis of sediments and waters included chemical elements not considered before. High Li (0.8 mg/L) was founded in the Toro river water, and high Co (420 ppm) and Y (120 ppm) associated to high Cu and Zn (but low As) in fine sediments of the Incaguaz river. This fact may point to a different type of an unknown mineralization in the basin.

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High-altitude Chilean hot springs: hydrogeochemistry characterization and biogeological relationships in Lirima, a window to early Earth

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A considerable number of geothermal systems have been identified along and across the Central Andean Volcanic Zone. Lirima hot springs are located above 4,000 m a.s.l, in the Tarapacá Region of northern Chile. The conditions found in these systems resemble those of early Earth and are linked to the evolution of the global elemental cycles. High altitude hydrothermal systems contain essential biogeological fingerprinting of the history of the biosphere, due to the extreme environmental variables and low anthropogenic disturbances.

Here, we aimed to understand how biogeochemical processes in Lirima hot springs determine the structure of microbial communities inhabiting the system, using geochemical, isotopic, and physical and chemical characterization of water and sediments samples. Our results show a high gradient of physical and chemical parameters in the Lirima thermal ponds, with temperatures ranging from 52 to 75°C, pH between 6.3 to 7.2, dissolved oxygen from 3.9 to 4.4 mg/L, total dissolved solids (TDS) between 864 to 879 mg/L and electric conductivity (EC) between 1,731 to 1,756 µS/cm. Overall, pH is inversely correlated with water temperature and a positive correlation is observed between pH/DO and EC/TDS. Dissolved cations ratios are Na^+>Ca^{+2}>Mg^{+2}, while for the anions are SO_4^{-2}>Cl^->HCO_3^-, with a predominance of Na^+, SO_4^-, and Cl^-. HCO_3^-/ SO_4^{-2}/ Cl^- contents show the occurrence of H_2S dissolution and an intermediate classification of steam-heated and volcanic waters, indicating a contribution of hydrothermal fluids.

We determined strong relationships between the hydrogeochemistry and biological indicators. Overall, microbial communities were distributed according to physical and chemical parameters, were temperature and pH were the main factors driving the community structure. For instance, colder ponds are dominated by phototrophic bacteria (i.e., anoxygenic photosynthesis processes) conforming microbial mats, and hottest ponds by chemolithotrophic microbial communities from the Bacteria and Archaea domains.

We propose that high-altitude hot springs represent an excellent model to elucidate the processes occurring between geological, physical, and biological dynamics. This study will contribute to the understanding of biogeochemical cycles and how these fragile ecosystems could be affected and modified in response to the accelerated climate change.

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Oral Presentations

Technical Session 7

Isotopic geochemistry: New uses in applied geochemistry

Sr-Nd-Pb isotopes from the Chollay Plutonic Complex, a Triassic non-compressive arc batholith of the SW margin of Gondwana

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The geology of the Chilean Frontal Cordillera (28-31°S) is dominated by lower Carboniferous-Upper Triassic intrusives, which account for prolonged and continuous magmatism along the southwestern margin of Gondwana. The study of these batholiths allowed to differentiate at least two geotectonic cycles that correspond to the Gondwanan cycle (Carboniferous-lower Permian) and the Pre-Andean cycle (middle Permian-Lower Triassic). Gondwanan plutons present characteristics typical of arc magmatism generated on an advancing margin. On the other hand, the plutons of the Pre-Andean cycle correspond to highly evolved and homogeneous calc-alkaline granites with a local presence of A-type granites. Pre-Andean magmatism has been interpreted as the result of extensive crustal melting, generated by the rise and stagnation of basaltic magmas at the base of the crust after the end of subduction along the western margin of Gondwana. Recent studies carried out on exposed magmatism in northern Chile and Argentina (18-40°S) suggest that subduction was continuous since the Carboniferous presenting changes in the deformation style of the upper crust: from a context dominantly compressive (Carboniferous-early Permian) to one transtensional (middle Permian-Jurassic).

This work focuses on the largest pre-Andean magmatic unit and corresponds to the Chollay Plutonic Complex: a set of plutons incrementally emplaced between the Lower-Middle Triassic, synchronously with the opening of forearc and backarc basins along the SW margin of Gondwana. This complex intrudes Paleozoic plutonic and metasedimentary units and presents a wide compositional variety that ranges from gabbros to granites, with monzogranites and granodiorites being the most common lithologies. We present new isotopic data of whole-rock (Sr-Nd-Pb) which, together with field, petrographic, elemental geochemical and mineral chemistry data, in order to understand how this large-scale and mainly granitic complex was built in a convergent context but dominated by extensional tectonics.

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Isotopic and geochemical tools to monitoring ecosystem services provided by native forest: The case study of the Nonguén National Park in the coastal area of south-central Chile

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The Chilean population is highly vulnerable to the current climate crisis and to one of its most significant phenomenon at the local scale: the decade-long drought that affects the south-central territory, especially the coastal lands. Alongside the decline in total water precipitations and surficial temperature increase that results in lesser water reserves, the country’s economic and political model of development is a key factor that combine with the physical variables to exacerbate the negative impact of climate change on human infrastructure and habitat. In the coastal area of south-central Chile, more than six decades of government-subsidized replacement of native forests by fast-growth exotic plantations (Pinus radiata and Eucalyptus globulus/nitens) has likely triggered, or at least increased, extensive soil degradation and affectations of main watersheds. This extensive replacement has seemly decreased water provision and increased nutrient and sediment loss to streamflow over the years. Recent studies in this area have pointed out to the higher efficiency of native forest in moisture retention and water provision compared to exotic plantations (1).

The tools used to quantitatively assess the ecosystem services provided by native forest are mostly direct measurements of daily streamflow, runoff, atmospheric and water pressure and wells. We tested the use of geochemical proxies as additional tools for monitoring the efficiency of the ecosystem services of water provision and water quality. The case study is the "Nonguén National Park", a 3000-ha relict patch of the sclerophyllous forests of central Chile located in the metropolitan area of Concepción surrounded by exotic plantations and agricultural lands, that feeds the Nonguén river, an important supplier of drinking water to ~100,000 inhabitants. We measured δ18O, δD, nitrates/nitriles, phosphates and pH-Ec in 27 locations of tributaries and nested points of the main river at the beginning of summer, autumn, winter and spring seasons. To characterize the watershed, it was further divided in three smaller catchments: the southern catchment (SC) with only native forest (but connected to agricultural lands), the eastern catchment (EC) with both native forest and exotic plantations and the northern catchment (NC), which is also the downstream flow area, with only exotic plantations.

Our results show that during the autumn and winter seasons there is a slight difference between surficial water coming from SC and EC-NC, with the former exhibiting the largest deviation from the Local Meteoric Water Line (LMWL), suggesting higher retention rates and larger contribution from groundwater. Nutrients on the other hand, are slightly more diluted in the samples of the SC and EC, recording a significant increase downstream, where exotic plantations and urban activities dominate. Samples taken during the spring and summer seasons (the driest period of the year) further record this difference, with lager isotopic deviation from the LMWL in waters sourced in the native forest area (SC), compared to those where exotic plantations are present. Within the SC a very significant decrease in nutrients is observed from the upper part of the catchment to the output area, bordering to the NC, suggesting that the less degraded soil in the native forest area acts as a more efficient system of ion exchange, helping to retain nutrients from waters.

We propose that these cost-effective geochemical tools may be part of a more diverse toolbox of chemical proxies that would help to monitoring the ecosystem services provided by areas with native forest dominance as well as in future implementation of nature-based solutions for water provision and quality.

(1) Lara et al. (2021). Hydrological Processes 35(8): e14270.

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The application of U-Pb age dating of in-situ carbonates by LA-ICP-MS to resolve timing of fluid flow in the Michigan Basin in southern Ontario

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U-Pb dating of calcite and dolomite is an emerging tool in exploration that has been used to constrain metallogenic models and directly date hydrothermal ore events. In low-permeability sedimentary rocks that have the potential to capture carbon or contain and isolate nuclear waste, secondary dolomite, calcite, and silica cements in veins and vugs preserve a history of past fluid movement and can provide important constraints on the hydrogeological stability of the sedimentary sequence. We present a case study of U-Pb age dating these in-situ secondary minerals by LA-ICP-MS applied to drill core taken from the eastern flank of the Michigan basin in southern Ontario. Downhole sections were analysed using LA-ICP-MS and ages confirmed by ID-TIMS. Secondary calcite from >650 m deep Ordovician carbonate rocks yields a

Silurian age of 434 ± 5 Ma, while calcite cement in the Silurian unit above and secondary dolomite and silica cements in the Cambrian sandstone unit below have similar younger ages of 318 ± 10 Ma and 320 ± 10 Ma respectively. We show that 1) shallow vein ages at depths <200 m reflect Cretaceous and Cenozoic movement of meteoric and glacial water 2) Ordovician hosted fluids are most likely a combination of infiltration of seawater from overlying evaporitic basins and hydrothermal solutions that infiltrated from below and remained unperturbed despite regional post-Paleozoic tectonic events and 3) the Cambrian sandstone has a distinctive initial common Pb end member, which, when combined with previous hydro-geochemical and fluid inclusion studies is interpreted to record episodic migration of saturated hydrothermal brine.

These absolute ages tighten constraints of hydrogeological models of subsurface fluid flow and provide important insight into the migration of different fluid bodies through the sedimentary section as a corollary to previous hydrogeochemical and fluid inclusion studies. This case study exemplifies the paragenetic understanding required to interpret in-situ carbonate ages, with implications for their potential application to resolve syn-mineralization alteration assemblages of MVT, SEDEX, and the distal fringes of porphyry deposits.

Oral Presentations

Technical Session 8

Linking geology and geochemistry to viticulture and wine / 1st. IGVWS2022

Vine capacity, abiotic stress severity, and wine composition of a non-irrigated vineyard along an Inceptisol catena in the Itata Valley

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Many vineyards in the Itata Valley are head-trained and planted along catenas, showing low uniformity in yield and wine quality. A study was conducted in a 3.5 ha non-irrigated vineyard (*Vitis vinifera* L. cv. País), planted across an Inceptisol catena in Portezuelo, Ñuble Region, Chile for two consecutive seasons (2018-2019). Vineyard elevation ranges from 146 m above sea level at the summit to 135 m at the footslope. Two vineyard areas were selected to represent the elevation and water availability range along the catena (SD: Summit-dry; FW: footslope-wet). Yield components, vegetative growth parameters (Leaf area index: LAI and pruning weight), and abiotic stress variables (midday stem water potential: Ψ_{stem} and visible atmospherically resistant index: VARI) were measured in each area. Basic wine composition was determined as alcohol percentage, titratable acidity, and pH. Vines from both areas exhibited severe water stress (Ψ_{stem}<-1.0 MPa) and low VARI values (±-0.14) at harvest. The yield was 52% higher in FW due to a greater number of bunches and berries per bunch. The sugar per berry positively correlated with crop load, the LAI/Yield ratio, and the Ravaz index in the FW area. Conversely, these correlations were negative in the SD area. Results suggest that SD plants were photosynthetically limited by the source (leaves), while FW plants were limited by the sink (bunch). More alcoholic and less acidic wines were obtained from the SD area, which probably reflected the lower canopy density (LAI_{SD}=1.0 vs LAI_{FW}=1.4). Consequently, a detailed characterization of vine capacity is essential to adapt cultural management to topographic variability along a catena.

Mineralogical influences in soil properties: Data and insights from Chilean vineyard soils

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We studied four vineyards of Central Chile in order to characterize the mineralogy of parent materials, total soil (clay + silt fraction) and clay fraction in cultivated and uncultivated soils by means of petrographic and X-ray diffraction (XRD) analysis, with the aim of recognizing how the mineralogy or particular clay minerals can determine some soil properties and agronomic aspects of the soils.

The soils of the vineyards located in Casablanca and Santa Cruz have similar mineralogy since they are formed from a granitic parent material, while the soils of San Antonio derived from marine sedimentary rocks and San Javier soils formed from an acidic volcanic tephra, presenting a particular mineralogy.

The clay minerals of granitic soils consist of kaolinite >> illite >> vermiculite (± smectite). This mineralogy explains the low cation-exchange capacity (CEC) and organic matter (OM) content measured in these soils. In addition, cultivated granitic soils have more acidic conditions than the uncultivated ones, probably due to greater leaching favored by irrigation in permeable soils (average of clay/sand ratio=0.12-0.21). On the other hand, San Antonio soils were cracked in dry season, having a high CEC and OM content, coinciding with higher proportions of clay fraction (30- 44%). In this site, the clay fraction is mainly composed by montmorillonite, an expansive and high CEC clay mineral, which generates soil cracking because of the shrink-swell capacity. In addition, that property could be responsible for a low development of fine roots, influencing grapevine yield components. Similar conditions, although with lesser intensity, were observed in San Javier soils, in which the occurrence of montmorillonite generates less soil cracking, possibly because of the non-crystalline clays (allophane and imogolite) predominance and loam textures (higher silt content) of soils.

In terms of top-quality wines, it is expected that soils with low contents of OM and efficient permeability, as seen in granitic soils of Casablanca and Santa Cruz, will generate better conditions to keep the plant in a moderate water stress, as well as control of vigor (vegetative growth). These conditions allow to trigger the secondary metabolism in the plant, responsible for the generation of organic compounds such as polyphenols, aromatics, and tannins, which produce color, taste and aroma in wines.

The terroir of Carignan in the Maule Valley: from the soil to wine

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Carignan is one of those minor cultivars that have had a major resurgence in the Chilean wine industry due to its high enological potential. This variety, together with other autochthonous grapevine varieties, makes up a unique heritage in Chilean winemaking, which has given a new identity to the country on the world wine scene. Thus, this work summarizes the effects of terroir of the Maule Valley on the typicity of Carignan. In general, locations close to the eastern watershed of the Coastal Range are at higher altitudes and have lower heat summations during the growing season. Carignan grapevines growing in these sites present high concentration of several amino acids and volatile compounds in grapes and wines. Contrary to this, locations on the west and north are at the lowest altitudes and have the greatest heat summation. In these zones, Carignan grapevines provide grapes and wines with a high alcohol and phenolic concentration. Therefore, Maule Valley provides unique pedoclimatic conditions that allow differences in the composition and style of the Carignan wines.

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Geo-winegrowing characterization from the Atacama to the Aysen regions of Chile

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Chile is a country that stands out for its winegrowing industry, however, this activity follows traditional practices, where the relationship of geology with the formation of soils and how this interaction affects the development of the vine is still little understood. It is in this context that this work aims to carry out a geo-winegrowing characterization of Chile for the purpose of generating geological and geomorphological criteria for the evaluation of vine cultivation areas.

With this objective in mind, a geo-winegrowing map was made, at a 1:1,000,000 scale, using the geology generated by SERNAGEOMIN and published in 2004. The study area was delimited to the 17 wine valleys established in Decree No. 464, which determines the Chilean designations of origin. These valleys were modified considering a geomorphological criteria through the incorporation of hydrographic basins provided by the General Directorate of Water (DGA). The valleys are divided into the wine regions of Atacama, Coquimbo, Aconcagua, the Central Valley, South and Austral. For each of these regions and their respective valleys, geology was described on a regional scale, divided by within the morpho-structural Principal Cordillera, Central Depression and Coastal Cordillera. In addition, in order to explore the incorporation of more detailed information, the Casablanca Valley is selected to carry out a 1:100,000 scale map based on the Valparaíso-Curacaví area, in order to differentiate the various types of geological units. Also, in the Copiapó Valley, a clay mapping was carried out using ASTER satellite images to recognize the distribution of the minerals illite, kaolinite, montmorillonite, and vermiculite. Finally, for six valleys defined as priorities (Casablanca, Maipo, Rapel, Maule, Curicó and Itata) slope and slope orientation maps were made.

The valleys are characterized by north-south and east-west variations of geological and morpho-structural units and, although valleys of the same wine region have similar characteristics, each of these presents unique particularities that differentiate them.

Based on the hydrographic basins and geomorphological characteristics, three wine valleys are proposed in the Aysén Region subject to their meso-climatic conditions. Each of these feature particular rock units, which can represent interesting terroirs in a climate change scenario.

Thus, the understanding of geological characteristics focused on the Chilean wine valleys, may allow the generation of criteria for evaluating agricultural properties.

Viticultural potential of the Nagche territory of the Araucania Region

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Funded by National Indigenous Development Corporation (CONADI), this study was carried out in the eastern valley of the Nahuelbuta mountain range, with the objective of exploring the viticultural potential of lands that have been returned to 13 Mapuche communities through Law 19,253. Carried out during the 2020-2021 season, it covered approximately 6,000 hectares located in the communes of Los Sauces, Traiguén and Galvarino. A climatic description was made in the study area, a preliminary analysis of the spatial variation of the minimum air temperature using satellite images. It also included trial pit in each study sites from which a description of the morphological unit, geomorphology, geology, and edaphic characteristics was made. It was found that all the zones are considered as cold climate and therefore only short-cycle cultivars are adapted. However, in the near future (2020-2035) the zone will have a temperature increase between 0.5 and 0.6°C. A climatic constraint is the occurrence of spring frosts. The study area presented six macro-units: Phyllites, Granitoids, Sandstones, Alluvial-volcanic ash, Alluvial-metamorphic and Volcanoclastic Deposits. The soil macro-units present mainly clayey texture with bulk density between 1.2 to 1.3 and usable moisture between 11 to 20% of the soil volume, also present low soil fertility indicators in relation to organic matter and macronutrients. The area has conditions that would allow the production of quality wines with identity.

Geochemical and Mineralogical Changes during Soil Development: Preliminary Study of a Brunisolic Soil from Nova Scotia

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Soil horizons develop due to chemical and physical gradients at the geosphere/ atmosphere/biosphere/hydrosphere interface that is a soil. These horizons are commonly poorly understood because they tend to be thin, poorly crystalline, and fine-grained, making their geochemical and mineralogical compositions difficult to characterize. Historic geochemical investigations of soils have generally employed small sample numbers, restricted element suites, and limited digestion methods, and have largely ignored the heterogeneity of the parent material. As a consequence, historical attempts at characterization of horizon development have provided marginal geochemical and mineralogical insight.

Fifty 30 x 30 x 4 cm soil samples comprising a 2 m thick vertical profile through a dystric (< 5.5 pH) elluviated (w/Ae horizon) brunisolic soil developed in a ~5 m thick homogeneous, fine-grained glaciofluvial sand in Nova Scotia's Annapolis Valley were collected to investigate soil profile development. This site was chosen because of its easy accessibility via excavator, lack of historical disturbance, old-growth species consistent with a mature Acadian forest, and because the primary mineralogy of the sand (quartz, feldspar, biotite, and muscovite derived from the peraluminous South Mountain batholith) is relatively simple. Variables measured include: soil density, moisture, texture, Munsell color, pH, conductivity, magnetic susceptibility, ICP-ES/MS geochemical analyses of $LiBO_3$ fusions (10 major/33 trace elements), aqua-regia digestions (36 trace elements), and deionized water digestions (30 major/trace elements), total carbon and sulphur analyses by infrared absorption (LECO), Penfield H_2O^+ analysis, and smear mount XRD analysis on the -63 um fraction of each sample.

Results indicate that parent material heterogeneity persists despite all efforts, as different textures and modal mineralogy within the sand were encountered at various depths. However, molar element ratio analysis could model/circumvent this variability, allowing an understanding of quartz, alkali feldspar (OR_{90}), apatite, Na-phengite, and ferroan kaolinite material transfer within the soil profile. The depths where biotite breakdown took place via Fe oxidation, apatite dissolved, and the locus of a kaolinite-bearing sub-soil aquifer occurred could be identified. Surprisingly, only small amounts of feldspar hydrolysis occurred, likely due to limited weathering since the glacial retreat from Nova Scotia.

Geology, mineralogy, and geochemistry in viticulture

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The concepts of Terroir in viticulture and wine production make reference to various aspects of vine cultivation, climate and site, that when combined can determine specificity of origin, hence provide uniqueness of product. Despite the previous, aspects such as geology, geomorphology, mineralogy, geochemistry, hydrogeology, among other site specific conditions, are not usually considered for the definition of specific Terroir parameters, most likely because the influence of these conditions on the cultivation of vine is unclear, much debate respect to the impacts of these on the quality of wine. Despite the debate, in the cultivation of vine much attention is paid to soil and soil forming processes. From a geological perspective, soils form along the contact of the lithosphere with the atmosphere, hydrosphere and biosphere, a result of complex chemical, biochemical and biological processes that involve interaction of the rock substrate with water, air, plants, microbes, along the critical zone, all these processes greatly controlled by local climate and site conditions.

Considering a typical soil profile, from substrate to the C, B and A horizons, the mineral composition, texture, and structure of the parent material from which soils form, will have physical and chemical effects on water-rock-plant interactions and on plant growth and activity. Physical and chemical effects such as permeability, access to water, drainage velocity, water retention, chemical and mineral composition and physicochemical properties of water, mineral dissolution and nutrients availability, are all defined by the local site specific conditions combined with climate. Study of several vineyards of central Chile demonstrate that overall, in densely cultivated valleys, relevant variations of substrate and soil distributions occur, even at small scale, which are a function of the distribution of the main rock and regolith units, all related to the geological, geomorphological and landscape evolution processes. These local variations have direct implications and relation to cultivation zoning, an aspect that is well recognized in viticulture soil classification.

Climatic study of the Chilean viticultural production zones over three decades

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Chile is characterized by offering high-quality vitivinicultural products and for its renowned viticultural valleys, with specific and diverse terroirs. At today, Chile has been considered vulnerable to climate change, which has brought a major concern to the national vitiviniculture. This research aimed to analyze the trends and climatic variability of the Chilean viticulture over three decades (1985-2015), evaluating meteorological, bioclimatic and risk indices in forty-seven stations. Meteorological data indicated that the warmest zone was Atacama, while the coldest was Aysén. The rainiest region was Austral, while the driest was Arica y Parinacota. Growing-season indices (GST, GDD and HI) showed that Central Valley was warmer than Arica y Parinacota, whereas, this latter, presented higher sum of spring temperatures (SONMean and SONMax). Atacama presented the highest risk for T>30°C, whereas Central and South Valleys for T>35°C. The highest frost risk was in Aysén, while the lowest in Arica y Parinacota. In general, Min T decreased by 0.33 ºC, while Max T increased by 0.83ºC. None of the trends for PP presented statistical significance. GST, GDD, HI, BEDD, SONMean and SONMax increased by 0.58ºC, 118.29 heat units, 140.57 heat units, 79.72 heat units, 8.42 heat units and 45.17 heat units, respectively, while CI decreased by 0.19ºC. Some stations that presented negative trend on CI coincided to the highest Max T. Locations in Coquimbo and Aconcagua valleys changed from intermediate to warm climate. Locations from Coquimbo and Central valleys changed from warm to hot climate. Quilaco changed from cool to warm climate, while Osorno changed from without classification to cool climate. PCA analysis reported that meteorological variables were related to the distance of the site to the Pacific Ocean. This information is of importance for the national industry and may allow to define mitigations strategies facing global warming.

Application of a weak leach as a measure of bioavailability in vineyard soils for management of soil nutrient levels in British Colombia, Canada

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Assessment of soil nutrient levels is critical for the management of vineyards and optimal vine development. The key question is how this can be measured consistently in the field. Ideally, the extraction should be able to extract a large number of elements in a range of soil types. Many partial extraction schemes have been used to assess bioavailability, but none match the elemental coverage of the Mobile Metal Ion (MMI^{TM}) method that was used by Mann et al. (2015) in a low density continental wide survey of agricultural soils in Europe to measure bioavailability. Up to 53 elements can be measured by sensitive ICP-MS instrumentation which is necessary to determine the many elements that occur at low levels; MMI^{TM} extraction levels range from 0.04 % for Ti to 36.8 % for Ag compared to aqua regia extractions on the same soils. Samples are collected at depths of 10-25 cm which is within the root zone of the vines.

The MMI^{TM} technology has been applied to a number of vineyards in the Okanagan Valley in British Columbia, which is one of the leading grape growing regions in Canada. Examples will be discussed from several vineyards where bioavailability surveys have been carried out to assess soil nutrient levels and profiles. Nutrient deficiencies recognized in any part of the vineyard can be corrected to allow even vine growth and grape development. The soil chemical data can be correlated with other multispectral data collected by drones. Correction of nutrient deficiencies is automated through a Fertbox developed in conjunction with the University of British Columbia.

Financing: SGSVintalityGeotronics

Reference

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Oral Presentations

Technical Session 9

Analytical geochemistry technologies and quality assurance / quality control

Standardless quantification with micro-XRF – are we there yet?

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Sample analysis during any geological campaign for the exploration of new ore deposits inevitably involves the quantification of the elemental composition of samples. Traditionally, what is considered quantification is the comparison of the sample´s elemental composition against known reference standards. This is especially true for bulk-XRF, an analytical technique commonly used for determining the major, minor, and trace element composition of geological samples. However, for almost 70 years the theoretical foundation exists to be able to do XRF quantification without standards, purely based on the so-called fundamental parameters (FP), which describe the known probabilities for all physical interactions between the X-rays and the sample.

When quantification is based on the use of reference standards, at least 4 potential problems arise:

1. For less common sample types or concentration ranges, there are no appropriate certified reference materials.
2. For methods with low spatial resolution many samples are non-homogenous within the analytical volume and, therefore, the samples do not have a defined composition and thus any quantification must be used with a large intrinsic uncertainty.

3. The certified composition (if one exists) may be based on an older set of reference samples, which themselves may have been quantified using even older standards or calculation models, and so on.
4. Even if the standard is perfect, the real sample often is not, and thus certain assumptions may not apply.

The first and most prominent issue, can be overcome by basing the quantification on the known physics instead of reference standards. The second problem is avoided when using analytical methods, such as micro-XRF, with sufficient spatial resolution to resolve inhomogeneities. In Micro-XRF a very small X-ray spot is used to scan the element distributions along the surface of relatively large samples, such as hand samples and drill cores. In combination with FP quantification, information on concentration variation at the micrometer scale can be obtained.

The quality of standardless quantification today rivals that of a standard-based quantification, but it is much more flexible. Specifically, any sample can be analyzed without the need of an initial calibration with the expectation of a similar quality of quantitative results compared to traditional standard based quantification. Furthermore, this method can be used to assess the useability of a set of geological reference samples.

Blank Analyses in Geochemical QAQC: How to Get Something from Nothing

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Data quality assessment samples used to determine if geochemical analyses are ‘fit for purpose’ include: (*i*) reference materials, (*ii*) field, preparation, digestion, and laboratory replicates, and (*iii*) blanks. These samples assess the essential measures of data quality: accuracy and precision and can detect the presence of contamination. Researchers have developed sophisticated numerical procedures to assess accuracy and precision (*e.g*. Thompson & Howarth error plots, Shewhart control charts), but blanks are commonly only examined to flag above detection concentrations, thus identifying when contamination may be present. Fortunately, blank analyses can be used for other purposes as long as the analytical laboratory provides the element concentrations in un-truncated/un-rounded (raw) form.

Calibrations that obtain element concentrations from analytical responses presume that blanks have, on average, a concentration of zero. With raw geochemical results and a normal distribution measurement error assumption, statistical tests can be used to rigorously assess this hypothesis. When rejected, the non-zero blank mean serves as a background correction factor that can be subtracted from the data to improve its quality.

Raw blank analyses can also be used to assess whether an analytical batch has been reported with an appropriate detection limit, defined as the concentration where analytical error is 50 % (equal to two standard deviations of the blank analyses). At this detection limit, the magnitude of the reporting interval that introduces an acceptable amount of round-off variance (5 or 10 %) is also calculable. This allows geoscientists to properly truncate and round laboratory-supplied raw element concentrations in a manner that reports these data with the highest statistically justifiable resolution, a feature not necessarily achieved using laboratory truncated/rounded concentration data.

Even with truncated/rounded results, geoscientists can statistically test whether the number of blank analyses exceeding the laboratory detection limit is statistically expected, a procedure that effectively flags batches where inappropriate detection limits have been used by the laboratory, or where outlying (contaminated) concentrations are present. Clearly, important data quality information can be obtained from blank analyses, provided they and their associated data, are supplied in raw form by the analytical laboratory (*i.e.,* ***you can get something from nothing!***).

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Certified Reference Material Accepted Values and Tolerances: Some Idle Thoughts and an Idea or Two

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Certified reference materials (CRMs) are used to assess the quality (accuracy/ precision) of geochemical concentration estimates made by geochemical laboratories. Accepted values (means) and tolerances (standard deviations) for CRMs are derived using round robin analysis of sub-samples at multiple geochemical laboratories using an ostensibly common analytical procedure. Unfortunately, CRM sampling, digestion, and analysis procedures vary substantially, as many labs implement custom analytical procedures they view as beneficial. These can have significant impact on the conformity of the CRM results.

Thus, round robin results for CRMs commonly exhibit between-laboratory variation that is far larger than within-laboratory variation. Unfortunately, the procedural differences employed by laboratories invalidate the use of the means and standard deviations as accepted values and tolerances for CRMs. Furthermore, round robin means can be biased high or low, creating substantial economic implications, and round robin standard deviations are generally larger than those obtained from CRMs in normal geochemical analysis, because these standard deviations are derived from many laboratories, not just the one laboratory used by that project. This results in CRMs passing QAQC thresholds for 'fit for purpose' analysis far more frequently than is expected, preventing the geoscientist from recognizing analyses with unacceptable errors.

To ensure that CRM analyses produce appropriate accepted values/tolerances, outlying analyses/laboratories are commonly excised from consideration. Unfortunately, outlier recognition methods used for this purpose vary substantially, and have not been effective in removing inter-laboratory variation. Furthermore, while outliers are identified, no corresponding cause is recognized to justify eliminating them from consideration, invalidating their excision.

Clearly, changes to procedures producing CRM accepted value and tolerance production methods are necessary. A possible approach to remove unacceptable inter-laboratory variation is demonstrated in this presentation, via a dendrogram-based method using distance measures equal to Mann Whitney U test statistical probabilities. In summary, geochemical analysis would benefit from the formation of a panel of stake-holders (geochemists, CRM producers, analytical laboratories, geologists, regulators) charged with identifying best practice methods to properly estimate CRM accepted values and tolerances.

POSTER PRESENTATIONS

Technical Session 1

Exploration geochemistry: Present and future challenges

Geochemical and Spectral Characterization of Lajitas South: New Target Located in The Maricunga Belt, Chile

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Lajitas South is a new exploration target located in the Maricunga Belt, Chile. It has not been drilled yet and is located 1 km south of the Lajitas target (a Au±Cu Porphyry-Style Deposit, with 425,300 oz @ 0.5 g/t Au), both within the Dorado Project. The company Angold Resources recently carried out an exploration campaign involving surface mapping, multi-element geochemical sampling, and spectral data collection (SWIR).

The main characteristic of the Lajitas South target is its marked annular geometry. Its mineralized centre shows evidence of Porphyry-type banded veins and is surrounded by an extensive area of lithocap. The lithocap's geochemistry is characterized by high concentrations of Se, Te, Bi and S, while the spectral data corroborate an extensive development of Argillic and Advanced Argillic alterations, with the presence of alunite, jarosite, kaolinite and smectite.

Its centre, and main gold-related Porphyry-type exploration prospect, is characterized by high values of Au and Cu in soils and rocks; its spectral mineralogy is characterized by the notable presence of white micas, chlorites, and smectites. In addition, elements Zn and Mn represent the periphery of the target, with chlorite and carbonate showings.

Using the Additive Index (a geochemical prospecting tool), different index elements representing the lithocap, porphyry, and periphery zones were generated. In addition, using these variables, the RGB-type process was also used to identify the transition zones of the target. Finally, the integration of spectral and geochemical data made it possible to characterize the valuable economic potential of the new target.

Sediment geochemistry of the La Serena Sheet, Coquimbo region

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In order to promote mining exploration and generate reference information for environmental studies, the National Geology and Mining Service of Chile, in its National Geology Plan, incorporated geochemical mapping of inorganic elements and compounds at a scale of 1:250,000. The Sediment Geochemistry of the La Serena Sheet corresponds to the fourth publication of the Geochemical Series of the Geological Chart of Chile.

This study presents and interprets the spatial distribution of the concentrations of 59 elements and chemical compounds of 699 samples of active and intermittent river sediments, collected from an area of 16,218 km^2, located between 29°30' and 31°00' S and from the coast to 70° 30' W. For each element and compound, a map of point concentrations and a map of catchment areas were generated.

The interpretation of the results allowed to identify:

- Six regional scale geochemical patterns mainly related to the different geological units and metallogenic provinces.
- Three regional scale geochemical anomalies with elevated concentrations of: 1) Fe-REE; 2) Cu, S, Sb and Hg; and 3) Zn, As, Ba and Cs.
- Local scale geochemical anomalies characterized by different combinations of Au, Ag, Cu, Mo, Pb, Zn, As, Sb, Cd, Hg, S, Se and Bi, mainly associated with the dispersion of debris from mining sites and tailings deposits.

It was also possible to recognize anomalies of prospective interest. These are natural anomalies, not associated with mining or other anthropogenic factors. The information obtained contributes to the search for new resources and the generation of environmental baselines for a sustainable regional development framework.

Financing: Programa de Cartografía Geoquímica, Plan Nacional de Geología, Servicio Nacional de Geología y Minería

Provenance Analysis of Placer Gold from Pureo Area, Southern Chile Coastal Cordillera

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Southern Chile Coastal Cordillera placer gold deposits are known and exploited since Spanish colony times. An example of these deposits is found in the Pureo area located at north of Valdivia, that is work by small-scale artisanal miners. Despite its well-known history of extraction that continues to this day, important knowledge about their origin and extension is scarce. A fundamental aspect still unknown regarding placers in this area is the primary source of the gold. Previous works have proposed that a large part of the gold in these placer deposits at regional scale comes from eroded deposits in the Principal Cordillera, although it has been pointed out that there are deposits in the Coastal Cordillera with a rather local origin. This work aims to identify possible primary sources of gold and the processes that formed the placer deposits in the Pureo area, by studying the morphological and chemical characteristics of the gold particles and integrating these characteristics to their spatial distribution. Their morphological characteristics were determined by acquiring a set of parameters that quantify the amount of transport that affected them, in addition to the accessory elements that they contain. Particle internal chemical characteristics were determined by studying polished cross-sections under optical microscopy, scanning electron microscopy (SEM) and electron microprobe (EMPA), where the gold alloy composition (in terms of major and minor elements) and the suite of mineral inclusions were obtained. Results on morphological characteristics of gold particles suggests a low amount of transport from its primary source (<15 km). High resolution chemical data from gold particles indicates the presence of two compositional populations that are distinguished in both their alloy composition (< 15 Ag wt% with up to 4 Hg wt% and > 15 Ag wt% with no detectable Hg) and the mineral inclusions that they present (Pyrite – Galena rich and Arsenopyrite rich), suggesting the presence of two different types of primary gold sources. These results suggest a local origin of gold in the Coastal Cordillera, where the possible primary sources are associated with massive sulfide deposits present in the Paleozoic – Triassic metamorphic basement and hydrothermal deposits associated with more recent Cenozoic intrusive activity. These conclusions have implications in exploration of undiscovered gold-bearing hypogene deposits (e.g., VMS deposits) in unexplored zones of the Coastal Cordillera.

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The application of physical and chemical characteristics of tourmaline from stream sediments: a novel tool in the exploration for porphyry Cu-Au-Mo deposits

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As the exploration for porphyry Cu-Au-Mo deposits has become increasingly challenging, the development of more effective techniques directed at detecting buried deposits has become critical. One methodology is to focus on key minerals, one of which is tourmaline, a robust, ubiquitous mineral in most mineralized porphyry systems. Overall, a combination of physical and chemical characteristics including 1) macro-color, 2) morphology, 3) inclusion populations, and 4) trace-element compositions are useful in discriminating between porphyry- versus non-porphyry–derived (or related) tourmaline in surficial sediments. These features are applied to tourmaline obtained from stream sediment samples (*n* = 22) from 16 streams derived from the unglaciated terrain proximal to the Casino calc-alkaline porphyry Cu-Au-Mo deposit (Yukon Territory, Canada). The obtained tourmaline occurs as two distinct morphologies: 1) individual blocky to prismatic sub- to euhedral grains (Type 1), 2) aggregates of radiating prismatic to acicular sub- to euhedral grains (Type 2). Type 1 grains display trace-element contents that reflect mixed origins including a mineralized porphyry origin as well metamorphic and pegmatitic (background) environments. Type 2 grains almost exclusively exhibit porphyry-derived trace-element chemistries (*i.e.,* high Sr/Pb ~150 *avg*. and relatively low Zn/Cu ~2.5 *avg.* values). In Canadian Creek, that directly drains from the Casino deposit, samples closest to the deposit contain >70% porphyry-derived tourmaline, while other streams in the region from unprospective drainage basins contain no porphyry-derived tourmaline. At the most distal sample site in Canadian Creek, ~20 km downstream from Casino, nearly 30% of the recovered tourmaline in the stream sediments is porphyry-related. This method has potential to be a strong indicator of prospectivity and applicable for exploration for porphyry Cu-Au-Mo systems in both unglaciated and glaciated terrains.

Distribution of Rare Earth Elements in Drainage Sediments of the Arica and Parinacota and Tarapacá regions, Northern Chile: preliminary results

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In the last decade, the National Geology and Mining Service incorporated a Geochemical Mapping Program into the National Geology Plan, which has contributed directly to the economic and environmental sectors of the country. Additionally, within the guidelines of the National Geology Plan is the development of innovative projects for the generation and divulgation of knowledge and geoscientific information. In this context, one of the objectives of the Geochemistry Unit is to develop the first Atlas of geochemical information of elements and inorganic compounds in sediments at regional scale (1:250,000) of northern Chile.

In particular, this work presents the preliminary results of the analysis of Rare Earth Elements (REE) distribution for the northern zone of Chile, which considered the chemical analysis of 2362 sediment samples, collected in the Arica, Pisagua and Iquique Geochemical Sheets. The area of interest covers approximately 40,630 km^2 and is located between 18°00' - 21°00'S and 69°00'W to the coastline, in the Arica and Parinacota and Tarapaca regions.

Boxplot diagrams were used to analyze the statistical distribution of REE values. From these plots, outliers were identified outside the boxplot whiskers, that represent negative and positive anomalies, compared to the mean REE concentration in the upper crust. Additionally, the data were analyzed using concentration maps, which allowed a visual inspection of the spatial distribution of the REE at a regional scale. Finally, the main geochemical patterns of this relatively large dataset, were identified by using an artificial neural network analysis.

Preliminary results show a geochemical differentiation at the regional scale, in which it is observed that sediments coming from the Coastal Range have a higher concentration of HREE. In addition, sediments from areas located in the Precordillera or in the Andes Mountain Range show a higher concentration of LREE.

Preliminary results of the Sediment Geochemical Database of the Taltal Sheet, Antofagasta and Atacama regions, Chile

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The Chilean Geochemical Cartography Program of the National Geology and Mining Service contributes directly to the economic and environmental development of our country. It allows the definition of prospective zones as well as defining geochemical baselines of sediments in Chile. Preliminary results of the sediment geochemistry of the Taltal Sheet are presented here. The area of the Taltal Sheet covers 19,500 km2, at a scale of 1: 250,000, and is located in the Antofagasta and Atacama regions (25°00' and 26°00' S and 69°00'and 70°45' W). This database contains geological, geospatial, and chemical information on 813 samples, collected from 764 sampling points. The samples correspond to active and intermittent drainage sediments (747 samples), fluvial terraces (6 samples), alluvial plains or pampas (59 samples), mining tailings (1 sample). Of these, 43 correspond to twin samples from the different sedimentary environments. Additionally, the database includes control samples, corresponding to 36 certified reference material and 34 pulp duplicates. The results of the chemical analysis were subjected to a quality control process, which included twin samples, pulp duplicates and standards. Results of the quality control demonstrate high precision and reproducibility of data. Most chemical elements (including Sum and LOI) have a low bias, less than 10%. It also made it possible to evaluate the effect of geological heterogeneity over the repeatability of a sample and to search in what way analytical precision decreased when concentrations were close to detection limits. This made it possible to ensure that the obtained data set for each of the lots had the necessary quality to be used in exploration of metallic minerals deposits and environmental studies, among others

The results are presented as concentration maps of the most common mineral prospecting elements in Chile. In addition, two geochemical indexes are calculated, the enrichment factor (EF) and the geoaccumulation index (Igeo). The results of the chemical analysis show various multi-element anomalies that are of natural and anthropogenic origin. Some of these define interesting prospective areas for mineral deposits.

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Apatite of detrital origin from Quipisca-Parca Canyon as an indicator of the presence of Porphyry Copper Deposits

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Comparing the cathodoluminescence (CL) and geochemical characteristics of detrital apatite from the Quebrada Quipisca-Parca sediments (Northern Chile) to those of apatite from the neighbouring Cerro Colorado porphyry copper deposit, highlights the potential of this common accessory mineral as tracer for porphyry deposits. Several studies have shown that apatite in porphyry deposits is sensitive to physicochemical changes that take place during interaction with hydrothermal fluids, the extent of which depends on the type of alteration and/or size of the intrusion. In this study, we compared twelve samples from perennial fluvial sediments of Quipisca-Parca Canyon and five samples from different hydrothermal alteration zones of the Cerro Colorado Intrusive Complex (CCIC). Primary unaltered apatite in potassic and propylitic alteration zones of the CCIC porphyry display yellow or brown-orange CL and contain high values of Mn, Na, Cl and S, while Ca is low. In these two alteration zones, altered apatite also occurs; it displays green CL and has low values of Mn, Na, Cl, S, and high Ca. The potassic alteration zone has a higher concentration of green luminescing apatite than the propylitic alteration zone. Apatite does not occur in the phyllic alteration zone, most likely due to the acidity of the latter, which dissolves the primary apatite. The gravels of the Qupisca-Parca Canyon contain several types of apatite. These include yellow and brown-orange luminescing varieties with high Mn, Na, Cl and S values and low Ca, i.e., CL and geochemical characteristics similar to those of primary apatite from the CCIC alteration zones. A green luminescing apatite also occurs in the sediments, with low values of Mn, Na, Cl and S, and high Ca, like the altered igneous apatite. A variety of detrital apatite with purple-pink CL was also found in the gravels. Its geochemical signature is similar to the primary apatite, but the CL colours do not correspond. This apatite could be the product of interaction between primary apatite and exogenous processes. The highest concentrations of green, i.e., altered apatite, in the gravels occur 4, 8 and 12 km to the west and 1 km to the east of the deposit, indicating a change in the direction and rate of erosion of the CCIC. Hence, our preliminary results suggest that apatite with green CL in sediments could be a good indicator mineral for the presence of nearby porphyry copper deposits, constituting a rapid and efficient exploration tool for this type of deposit.

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Use of Porphyry Indicator Zircons (PIZs) in sedimentary record as an additional exploration tool for buried porphyry copper deposits under a transported gravel cover from the Atacama Desert

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This work explores the potential of geochemical signatures and petrographic characteristics of detrital zircons coming from the sedimentary record of the Centinela district in Northern Chile to identify the presence of buried porphyry copper deposits under a transported gravel cover. The sampled sedimentary section was recovered from the pit of the exotic copper deposit of El Tesoro, located approximately two and four km west from the Esperanza and Mirador porphyry copper deposits, respectively. The sedimentary cover is composed of four different units, which correspond to Tesoro II, Tesoro III, Arrieros, and Recent gravels, deposited since the Late Cenozoic in an arid continental environment dominated by alluvial fans. All gravel units contain exotic copper mineralization with exception of Tesoro III gravels. In order to interpret the geochemical footprint of the investigated zircons, the Porphyry Indicator Zircon (PIZ) concept (Pizarro et al., 2020) is used. A PIZ need to comply with each of the following geochemical values: Hf > 8,750(ppm), Ce/Nd > 1, Eu/Eu* > 0.4, 10,000x(Eu/Eu*)/Y > 1, (Ce/Nd)/Y > 0.01, Dy/Yb < 0.3 and Th/U < 1 - > 0.1 and they usually show euhedral morphologies characterized by prismatic forms of type {110} and pyramidal forms of type {101} and {211}. The geochemical signatures and petrographic characteristics of the PIZ collected in the gravels are similar to zircons from Mirador and Esperanza porphyry copper deposits. The highest PIZ concentration coincides with the gravel horizons with exotic copper mineralization. PIZs in sedimentary records are therefore a good tracer of adjacent copper porphyries and represent a promising exploration tool for this type of hidden ore deposits in challenging areas covered by sediments.

Advanced PIMs Analysis: Case Study in the Domeyko Cordillera Comparing Optical and Automated Methods

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In recent years, various efforts have been made to increase exploration effectiveness in relatively mature areas such as the Central Andes of Chile. Among these are prospecting campaigns in covered areas, where uncertainty about the underlying basement geology is offset by ease of access and inexpensive operation.

On the other hand, a major effort arises when explorers pursue new search spaces in more remote and less accessible exposed areas. In this context, the analysis of porphyry indicator minerals (PIMs), obtained from stream catchment sediment samples, is an attractive tool in targeting and area reduction in extensive areas of interest (Averill, 2011; McClenaghan, 2011; Cooke et al., 2017). This tool, together with traditional bulk geochemistry of stream deposits, makes it possible to classify each catchment in terms of its prospectivity and magma fertility optimizing both budget and execution time of generative programs.

We present a comparison of a traditional optical approach with an automated solution to detect and analyze PIMs in stream sediment samples and discuss the advantages and disadvantages of their application to mineral exploration.

The differences are important in terms of type of minerals identified, counting and mineralogical characterization delivered by both methods. The automated solution offers significant advantages over traditional optical methods. It can detect almost all minerals in the sample, including alteration characterization for some of these, although the ability to detect some key trace mineral grains remains behind from the optical method advantage. In terms of physical characteristics, both methods provide gold grain shapes which relate to transport history of the grains and helps inferring the proximity to their source (Kelley et al. 2011; Girard et al. 2021).

Furthermore, the automated approach provides access to porphyry-related hydrothermal minerals that are typically not associated with traditional heavy mineral concentrates. Moreover, it reports the major chemistry of identified minerals which, with more research, opens the possibility to apply these as an exploration tool.

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Poster Presentations

Technical Session 2

New field portable technologies: Improving the analysis and turnaround times in exploration

Quantifying the invisible: pXRF analyses of three boreholes

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Portable X-ray fluorescence (pXRF) technology collects geochemical data at a fraction of the cost of traditional laboratory methods. Although the pXRF spectrometer provides concentrations for 41 elements, only a subset of these elements meet the criteria for definitive, quantitative, and qualitative data. However, high-quality pXRF data obtained by correct application of analytical protocols, can provide robust insight to stratigraphy and sediment characteristics that are often not observed by, for example, visual core logging, grain size analysis, and geophysical logging.

We present examples of geochemical results obtained from pXRF analysis of drill core samples from three boreholes located in Canada, that demonstrate:

1) Definitive stratigraphic boundaries observed in geochemical changes obtained from 380 analyses collected over 150 m of core, which intersects three Ordovician sedimentary formations and Precambrian granite. These boundaries could not be reconciled by traditional visual core logging methods.

2) Significant elemental concentration changes observed in 120 samples collected in each of two ~120 m deep boreholes located in a confined paleo-glacial foreland basin. The collected geochemical data provide insight to sediment provenance and stratigraphic relationships that were previously unknown.

3) Abrupt changes in the geochemical signature in a subset of 135 samples collected from a 151 m deep borehole intersecting Quaternary glacial derived till, sands, and a homogeneous silt and clay

succession. These data provide a platform for discussion on ice sheet dynamics, changes in depositional setting, and changes in provenance.

Results from each of these studies highlights previously unknown (invisible) geological information revealed through geochemical analyses. A significant benefit of using pXRF technology is refining sampling strategies in near real time and the ability to increase sample density at geochemical boundaries with little increase in analysis time or budget. The data also provide an opportunity to establish a chemostratigraphic framework that complements other stratigraphic correlation techniques, including geophysical methods. Overall, data collected with pXRF technology provide new insights into topics such as spatial correlations, facies changes, provenance changes, and depositional environment changes.

Investigating sources of data variability in short-wave infrared and visible to near infrared spectroscopy

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Short-Wave Infrared (SWIR) and Visible to Near Infrared (VNIR) spectroscopy is commonly used in mineral exploration for the identification of ore associated minerals to map the mineralogical halo of the ore system and identify systematic mineral chemistry changes to vector towards mineralization. Scalars applied to spectra produced by SWIR/VNIR spectroscopy target the wavelength, absorption depth, and absorption width for vibrational bond wavelength ranges. The geometry of these absorption features is related to incoming light energy being converted to kinetic energy as SWIR-active bond types (typically OH^- bonds) vibrate at key wavelengths. In other words, these bonds vibrate, absorb energy from incident light, and reflect the modified spectrum back. This allows for the identification of minerals containing diagnostic bonds, the speciation of which may be related to the P-T-X conditions surrounding a large hydrothermal cell and therefore valid as a vectoring approach. In addition to simple alteration mineral assemblage identification, the wavelength of a given bond may vary slightly in a phenomenon related to solid-solution composition of some minerals, which is also an effective vectoring method when applied carefully. As most measurements for SWIR/VNIR spectroscopy are carried out in variable field conditions, and some of these vectoring methods are sensitive to low-contrast changes in absorption wavelengths, this study set out to assess the sources of data variability in SWIR and VNIR spectroscopy.

Four analytical tests were conducted on mylar, minerals and drill core samples to examine variations related to: 1) lighting conditions; 2) instrument warmup time; 3) seasonal variance (environmental parameters); and 4) sample homogeneity. Results from this research show that lighting conditions had minimal impact on all scalars. Instrument warm up times showed that wavelength and absorption width scalars require significantly less time to stabilize compared to absorption depth scalars. A yearlong seasonal variance test encompassing environmental parameters like temperature and humidity showed absorption depth scalars correlated with ambient temperature and humidity, but wavelength and absorption width scalars were not impacted. By quantifying the variability related to these parameters, we aim to establish which parameters need to be controlled in practical application of these methods, and develop robust methods to numerically correct data, when possible.

Poster Presentations

Technical Session 4

Geochemistry applied to mineral characterization for geological, geometallurgical and resource modeling

Lidenbrock: A tool for recommending the location of next drill hole

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Classification of mineral resources is one of the most important steps in a mining project as the investments and development of mining projects depend on the quantity and quality of the mineral resources in the deposit. Mineral resources are classified into three categories (Measured, Indicated, and inferred) based on the level of uncertainty in the estimated model of deposit. One is always interested in reducing the uncertainty in the estimated model of deposit in order to increase the quantity of measured resources.

Drilling is the most common and frequent activity for reducing the uncertainty and as a result increasing the quantity of measured and indicated mineral resources. However, drilling is a costly activity and consequently it is indispensable to optimize the drilling process (Choose the best location for drilling to obtain maximum reduction of uncertainty).

In this poster, we present a software, called Lidenbrock, which recommends the best location for drilling the next drill hole based on minimizing the kriging variance and by taking advantage of particle swarm optimization algorithm. The capability of LIDENBROCK was assessed through a real case study. To this end, the results of resource classification by using the initial drill holes and five additional drill holes, recommended by software, were compared by the case when the locations of additional drill holes were proposed by an expert. The results demonstrated a considerable increase in the amount of measured and indicated resources by using the recommendation of LIDENBROCK.

LIDENBROCK proposed a new and complementary dimension to the mining and geological experts that, coupled with their experiences and operational considerations could yield important results in their exploration for improving resources estimates.

Types of wollastonite, and identification of host skarns and their protoliths at the St. Lawrence Wollastonite Skarn, SE Ontario

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Wollastonite skarns at the St. Lawrence deposit are hosted in granulite-facies calcitic +/- dolomitic marbles in the Frontenac terrane of the Grenville Province. The wollastonite ore has been interpreted to be formed by interaction of magmatic fluids derived from the 1167 Ma Leo Lake intrusion and the carbonate host. The wollastonite skarns are interlayered with marbles, siliciclastic rocks, quartzite, calc-silicate rocks, and cut by dikes. In this study, at least two generations of wollastonite were identified based on their textures and shortwave ultraviolet fluorescence properties: Type 1 occurs in massive aggregates and disseminations in marbles and is blue fluorescing; Type 2 is found locally filling veins, and is yellow fluorescing, attributed to replacement of Ca^{+2} by Mn^{+2}. Whole rock geochemistry indicates an enrichment in MnO, Fe_2O_3, and CaO. Three protoliths for the skarns were discriminated based on whole rock geochemistry: the first is characterized by Al_2O_3:TiO_2 from 14 to 42 wt%, its more enriched in SiO_2 (60-72 wt%), NaO (3-5 wt%), and Al_2O_3 (6-12 wt%) than the other skarns and is interpreted as an intermediate/felsic igneous protolith. The second type has the highest TiO_2 content (0.5-0.85 wt%) and elevated MgO, Fe_2O_3, and Cr_2O_3 concentrations (6-11 wt%, 2-6 wt%, and ~0.1 wt%) and is interpreted to be a calcareous protholith with a mafic contribution and comprises mainly the diopside-rich skarns. The third protolith has a composition intermediate between protoliths 1 and 2, denoting contribution of both mafic and felsic/intermediate igneous rocks, and includes most of the wollastonite skarns. Moreover, an empirical method was developed to classify the types of skarns based on the MgO and CaO ratios to assist in designing the geological block model. Four groups were categorized: (1) the wollastonite skarns, having >40 wt% wollastonite, high CaO (28-38 wt%), and low MgO (0-5.5 wt%), (2) Diopside skarns having >40 wt% diopside, intermediate-high CaO (15-32.5 wt%) and high MgO (5.5-12 wt%), (3) the siliceous skarns which have <40 wt% of wollastonite and diopside and low in CaO (0-28 wt%) and MgO (0-5.5 wt%), and (4) Mixed Skarns, with >40 wt% wollastonite + diopside, and are rich in CaO (28-38 wt%) and MgO (5.5-12 wt%). These findings will assist in identifying the various protoliths, categorizing the skarns and therefore the zones with enrichment in distinct calco-silicate minerals, including the wollastonite ore, which are not always evident to characterize and quantify during exploration and core logging.

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Copper-Bearing Normative Mineralogy Estimation at Antucoya Mining Company

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Mapping the spatial variability of copper-iron sulfide minerals in an ore-deposit is fundamental when it comes to support geology mineral-zones definition, selection of mineral processing alternatives and to build forecast models based on minerals rather than metals. There are several methods to estimate sulfide mineralogy (in a qualitative or semi-quantitative way) such as automated mineralogy, optical microscopy, X-ray Diffraction (XRD), Near infrared spectroscopy (NIR), visual logging, and sequential leaching. These methods cover a spectrum of possibilities on budget, turnaround time and deliverable's quality. Automated mineralogy allows a detailed characterization, but at a relatively high cost per test; on the other hand, chemical methods are less expensive, however, the amount of information is limited.

Antucoya Mining Company uses Partial Extraction method to map copper-bearing minerals within the deposit, the technique is based on the differing dissolution behavior of the main minerals. The normative mineralogy is semi-quantitatively in nature and it is considered a good alternative to identify main minerals in extended volumes, complementing more advanced methods. To improve the accuracy of normative mineralogy estimates, Partial Extraction was coupled with Near-Infrared Spectroscopy (NIR), and chemometrics models were developed using TESCAN mineralogy to achieve a more robust mineral characterization and ore-types definitions. Improved copper-bearing mineralogy was populated within the resource block model and spatial and geological consistency was assessed.

This work aims to show the upgraded methodology of copper-bearing normative mineralogy at Antucoya Mining Company and the benefits of build a comprehensive ore identification model. For this purpose, models based on TESCAN mineralogy, Partial Extraction (PtXt) and NIR were calibrated and chemometric models allows transforming chemistry and spectral data into normative mineralogy estimates.

Phenomenological approach to understanding geometallurgical properties from geochemistry and geotechnical properties

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Geometallurgy allows the integration of geology, mining and metallurgy with its fundamental purpose of maximizing Net Present Value (NPV) in the business. One of the critical processes in this area corresponds to comminution, characterized by the high consumption of energy and steel in grinding stages, it has been increasing due to a hardening of the deposits. Based on this, the need arises to be able to improve the predictions of geometallurgical variables of comminution (e.g. BWi, axb, DWi,) that allow not only to predict, as well to understand the phenomenon of rupture that occurs in those variables. To do this, incorporate parameters from other areas that can contribute to its understanding and prediction becomes relevant. The following research points to how the geotechnical properties obtained from simple compression, triaxial, indirect traction and point load index tests can contribute to the understanding and prediction of geometallurgical comminution variables, to do this the approach should be phenomenological more than empirical. In this approach, the influence of primary properties is considered in the first part, where variables such as geochemistry, lithology, alteration, mineralization or texture have an influence on the results of tests. To the above, the effect produced by the test conditions is also added, which are different for each methodology (e.g. L/D, stress rate, N° balls, etc.), these acquire great importance in the study, since the same test can be carried out under different breaking conditions, which imply a variation in its results. As conclusion, not only the primary properties must be considered in the model, but also the rupture conditions, which should be decoupled to understand the rupture phenomena in tests, whether geometallurgical or geotechnical.

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Poster Presentations

Technical Session 5

Environmental geochemistry: Closing the gap for sustainable mining and development / Mine Tailing Revalorization (Unesco-IGCP682)

Copper mobility in soils affected by anthropogenic activities in northern and central Chile

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In Chile, the main economic activity corresponds to copper (Cu) mining. Certain mineral processing plants and storage locations are found in or near urban areas which are potentially exposed to Cu contamination.

To understand the behavior of Cu in soil within and around potential anthropogenic sources, four historical mining sites were studied: Tocopilla and Antofagasta ports in Northern Chile, and Ventanas

Smelting and Las Tórtolas Concentration Plant in Central Chile. Surficial soil was sampled in concentric sampling patterns around these sites, and redox potential and pH were measured.

To infer Cu mobility, the fine sieved fraction (<63 µm) was analyzed with selective single digestions (F1-labile; F2-carbonates or pH sensitive; F3-reducible; F4-oxidizable; F5-residual); the quantification of each digestion was made using an ICP-OES. The degree of contamination and Cu enrichment were determined through environmental indices (geoaccumulation index-I_{geo} and enrichment factor-EF) via background compositions of local rocks and the upper continental crust. Results show that soils generally have circumneutral-pH and oxidizing conditions. Tocopilla, Antofagasta and Ventanas show similar concentrations of total Cu (median: 824 mg/kg; 645 mg/kg; 1345 mg/kg, respectively), indicating a severe enrichment and strong to extreme contamination near the anthropogenic facilities. In Las Tórtolas, Cu concentrations are lower than the previous sites (median 103 mg/kg), exhibiting moderate Cu contamination and severe enrichment. In this area, the concentration increases with the distance to different contaminant emission points and geogenically enriched areas. In general, all sites show that Cu is mainly linked to F5 (residual); however, it is related in lower proportions to all the other fractions. In Antofagasta, Ventanas and Las Tórtolas some samples are mostly associated with potentially mobile fractions (F1 to F4). The main conclusions to date indicate a strong enrichment and contamination of Cu in urban soils, and this is mostly linked to nearby anthropogenic activities. High proportions of Cu in F5 indicate an association to crystalline structures and low potential of mobilization. Also, F1 to F4 are present in all sites, indicating a weak attachment of Cu to soil which could be mobilized by eventual changes in physicochemical conditions.

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Geochemical assessment of sediments around tailings to determine the pollution contamination by metals at of the location of Alhué, Metropolitan Region, Central Chile

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Around the Estero Alhué (EA), located south of the Metropolitan Region (RM), there are tailings of different sizes and states of activity: Carén reservoir and La Florida mining tailings as active; and a small, abandoned tailings upstream of the EA. According to a previous study conducted by Castillo (2008), the EA river sediments are contaminated with metals/oids such as Ag, Pb, and Zn, where it is shown that Pb exceeds the general sediment average of Sparks, 1995 exceeding the general average by 22.1 ppm and Zn by 40.6 ppm, as indicated in the results of Castillo (2008). For this research, the results were compared with Consensus-Based Sediment Quality Guidelines for Freshwater Ecosystems (MacDonald et al., 2000).

Considering the concern of the local communities and farmers of Alhué about the potential impact of pollutants at their crops, we think it is relevant to extend the geochemical characterization to the soils around some tailings, as well as evaluate the potential megadrought effect on the geochemistry of fluvial sediments, comparing them with studies from more than 10 years ago, prior to the megadrought.

A sampling of fluvial sediments and soils adjacent to mining liabilities will be carried out, which will be analyzed by acid digestion followed by ICP-MS.

From preliminary studies and local mining activity, it is expected to recognize polluting metals/oids, characterize their concentrations, their enrichment factor, their spatial dispersion near to the tailings, recognize and describe and to understand which physical and geochemical processes that control such dispersion. Finally, the results should demonstrate the level of geochemical impact of the tailings, highlight the more relevant pollutant and compare results with environmental sediment quality guidelines, since Chile does not have such kind of guidelines. We hope, in this way, to be able to make this information available to stakeholders so that they can make decisions about land use, meet the need to remedy them and ensure good management of river ecosystems.

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Environmental impact caused by the collapse of the Las Palmas Tailing Dam based on geochemical analysis of natural and tailing sediments

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In the last decades, despite the efforts made in geochemical characterization of tailings in Chile there is still a need for much more detailed studies in order to understand environmental impact of these mining liabilities. In particular, those generated by mine drainage and dispersion of contaminants in water and sediments. According to those necessities, this study pretends to give a first order approach to geochemical characterization by the use of scanning electron microscopy with energy dispersive spectrometer (SEM-EDS). Las Palmas Tailing Dam, located in Pencahue, Maule Region, was chosen as a study case because it is an emblematic example of an environmental pollution disaster generated by an abandoned liability. During the earthquake of 2010, the dam structure collapsed dumping 100,000 m^3 of material over 11 ha of agricultural fields and obstructing Las Palmas Creek (LPC).

Sediment samples were taken from tailings, surrounding soils and fluvial deposits. All of them presented Fe, Pb and Zn sulfides, which were associated with pyrite (Py), galena (Gn) and sphalerite (Sp) due to their chemistry and morphology. The presence of these primary sulfides in surrounding soils and LPC sediments is attributed to the 2010 material spill and subsequent transport. Moreover, Fe and K sulfates were detected in the tailings and LPC samples, which were interpreted as Jarosite, a secondary mineral commonly found in AMD environments. Despite this evidence and the favorable conditions for AMD generation from weathered sulfides and sulfides in the tailings, as measured in ponding waters around the tailing. The discharge to LPC did not modify the circumneutral pH (6.6 average) with low EC (382 µS/cm). It is expected that LPC should have high alkalinity content that can neutralize by mixing the low flow of polluted waters from the tailing.

In respect to the use of SEM, the recognition of metals such as Cu , Fe, Pb and Zn in the sediments is consistent with previous studies in the area (average mg/kg Cu: 705, Fe: 30.315, Pb: 4.216, Zn: 4.941 (CENMA, 2017)), which developed more specific geochemical analyses (XRD, AAS), proves that the use of SEM can be very a useful tool to collaborate in the geochemical characterization of areas with tailings.

Finally, it is concluded that 10 years after the collapse of the tailing, agricultural soils and river sediments are still polluted, affecting in unknown way agricultural production, the population and the ecosystems of the area.

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Poster Presentations

Technical Session 6

Water and hydrogeochemistry: Challenges in exploration, mining, and sustainable development

Can Chile extract Li from geothermal brines? Statistical approach to determine geochemical factors in Li enrichment

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Nowadays, there are known projects in the USA where, in addition to energy extraction, elements of economic interest such as Li are extracted from geothermal fluids. As a result, the question arises whether it is feasible to develop such hybrid projects in Chile to make more profitable the use of this energy.

The extraction of valuable elements from geothermal brines has been developed using different methodologies. The best researched and full-scale proven method for direct extraction of Li from brines is adsorption by metal oxides and hydroxides, as it meets efficiency and economic profitability criteria.

A preliminary statistical study indicates that the average of Li concentrations in geothermal fluids from the Tarapacá Region to the O'Higgins Region is 6.30 mg/l, the (min. 0.028 mg/l - max 46.28 mg/l at Tatio. In comparison with the concentrations of the fields studied in the USA, the range of concentrations in Chile is similar, so it would be feasible its development through an appropriate transfer of technology.

In this study, a statistical analysis of the geochemistry in high enthalpy geothermal systems in the north and center of the country is performed, particularly, of Li concentrations, in order to investigate if there are some geochemical conditions associated to high Li concentration. In addition, it will be analyzed if there is a correlation of geological factors with respect to the geochemistry of these systems. Through bibliographic research of geochemical data, a univariate and multivariate statistical analysis will be performed, searching for relationships between the geochemistry of geothermal fluids and Li.

The development of a hybrid system in Chile seems promising, although we consider that it is necessary to develop some exploratory criteria to find out systems with higher potential. Finally, it is still being necessary to estimate the influence of other factors that may affect the implementation of the extraction method. Therefore, further studies are needed to indicate the feasibility of technology transfer for the current Chilean context.

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Valuable elements in geothermal systems in Central-Southern Chile: preliminary selection of valuable elements and conditioning geological factors

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There are several projects around the world for the extraction of valuable elements from geothermal systems. In New Zealand they are conducting a review of technologies including lime softening and ultrafiltration and adsorption method, especially with those using inorganic-type spinel manganese oxides adsorbent, for silica and lithium mainly, as other compounds present in the geothermal fluid (precious metals, carbon dioxide, etc)[*4]. In the USA, research is currently being conducted on metal oxide and hydroxide adsorption technologies for the possible recovery of lithium, rare earth elements and other critical minerals from geothermal brines[*8].

In Chile, lithium production occurs by pumping brine from salt flats. Which can have a significant impact in local ecosystems, it is important to seek clean alternatives, such as the use of geothermal brines. Now, what geological factors affect the concentration of valuable elements in geothermal brines of Andean geothermal systems? And the concentration of which elements are affected?

The Andean volcanic arc includes thousands of stratovolcanoes, giant caldera systems and pyroclastic cones, arranged in four separate segments known as the Northern (2°N-5°S), Central (14°-28°S), Southern (SVZ; 33−46°S) and Austral (49-55°S) Volcanic Zones [*7]. Within the SVZ, there are several attributes that favour the formation of geothermal systems, such as: heat sources from magmatic processes, abundant precipitation in the main Andean Mountain Range and active fault systems [*5]. In geothermal brines, moderate to high concentrations of valuable elements are found depending on the predominant geological processes that enrich the thermal waters with certain elements of interest [*3; *10].

In the central zone of Chile (32.5°S–36°S) the thermal and cold springs in the Western Principal Cordillera were produced by the interaction of groundwater, flowing through permeable pathways associated with the Infiernillo fault systems, with a neutral to alkaline pH (7–9.3), and relatively low temperatures (<60°C). In the Eastern Principal Cordillera, the chemistry of the thermal fluids was controlled by the interaction with Mesozoic sequences enhanced by the addition of CO_2 rich gases, whose influence increases eastwards towards the active volcanic chain where mature hydrothermal reservoirs have temperatures 200 °C and have acid-neutral pH (<5.1-7.5) [*1]. In the central-southern zone of Chile (36°S-41°S), thermal waters are classified in three categories based on physicochemical parameters, (i) acidic sulphate waters, directly related to magmatic components, characterised by high temperatures (85°C) and acidic pH (<4), (ii) NaCl neutral waters, their chemistry is related by direct water-rock interaction and possess low temperature (55°C) and neutral-alkaline pH (7.2-9.3) and (iii) bicarbonate waters (HCO_3), related to intense shallow cathonic leaching processes, these possess low temperatures (<47°C) and alkaline pH (<6.2) [*10]. Finally, in Chilean Patagonia (43°S-49°S), thermal waters are classified into three groups of hot springs. (i) located along the coast controlled mainly by fjord water mixing, (ii) located in terrestrial areas shows magmatic-hydrothermal fluid input, and (iii) includes samples located in coastal areas that appear to be dominated by magmatic-hydrothermal fluid input with a minor influence of fjord water mixing [*5].

A geochemical database is constructed with published available data. A correlation of geological factors and water analysis has been performed using the statistical method of factorial analysis, used to identify similarities and differences between variables and samples, helping on the data interpretation [*2].

There are diverse geological factors in Central-Southern Chile that increase or decrease the concentrations of valuable elements. From the Metropolitan Region to the Maule Region, it is characterised by two belts of different ages and lithologies: (i) an eastern Mesozoic belt, composed of sedimentary rocks rich in limestones and gypsum in Central Chile, where the active volcanic arc is located; and (ii) a western belt of Cenozoic age containing basaltic to andesitic volcanic and volcanoclastic sequences. This geological setting controls the water chemistry of the region's cold and thermal springs, which are fed by the region, which are fed by meteoric water circulating through deep regional structures [*1]. From the Maule Region to the Aysén Region there are hundreds of thermal springs controlled mainly by (i) volcanism and the presence of (ii) two fault systems: the Liquiñe-Ofqui Fault System (LOFS) and the Andean Transverse Faults [*6]. Furthermore, in the Aysén Region, geothermal systems are influenced (iii) by the fjords and the LOFS fault systems, along with the volcanism of the area [*5]. The collected data contains analyses of alkaline trace elements such as Li, Cs, Rb; alkaline earth trace elements of Ba, Sr; metalloids such as B and As; and finally, transition trace elements such as Fe, Cu, Au, Ag.[*1; *9; *6].

Preliminary analysis of the collected data suggest that the concentrations of several valuable elements are most promising in inland areas, away from the influence of fjord water. Further correlations will be addressed in this work.

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A coupled isotopic-geochemical assessment of hydrological dynamic in headwater Andean basins in north-central Chile

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This contribution covers the use of isotopic and hydrochemical techniques to characterize the hydrology of four sub-basins of the upper Elqui river basin: Toro, Incaguaz, Cochiguaz, and Derecho. Whereas they are rather similar in their extension and basic physiographic characteristics, present different lithology, land use, and specific traits, which will allow having an interesting range of environmental conditions for the hydrological analyses with the proposed chemical and isotopic tools. Indeed, the Toro River basin drains the El Indio District area, which exhibits several advanced hydrothermal alteration zones that imprint an acid pH condition to the waters and important concentrations of sulfate, As, and metals such as Cu and Fe. The Incaguaz river basin is of interest as an important geochemical anomaly, specially related to high contents of rare earth elements in stream sediments and relatively high Li values in water, has been recently described (Oyarzún et al., 2022). Finally, in the Cochiguaz and Estero Derecho basins there is some minor agricultural activity in their downstream areas (e.g., below 2,000 ma.s.l.). In the headwater of Estero Derecho there is a “Nature Sanctuary” (January 2015), a private conservation area with Governmental recognition. A similar protection initiative has been recently adopted (March, 2022) for upper Cochiguaz. Thus, this setting (four basins) would allow to compare zones with and without (or with variable degrees of) human intervention and the effect of that on the hydrological dynamic (among other factors).

With the currently available data, it is possible to notice (in a preliminary way) the effect of the physiographic characteristics of the basins (altitude) on the isotopic signal (^{18}O, ^{2}H) of the surface waters. Also, a certain seasonality in the signal obtained is noted, both in the stable isotopes and in ^{222}Rn. With respect to the hydrochemistry, the different behavior of the Toro River (lower pH, higher EC, higher concentration of the different constituents) becomes rather evident. Also, it is noted that although in terms of the total amount of ions, the Derecho River tends to be the one with the lowest concentrations, in terms of the relative proportion of the different ions the Cochiguaz river display apart from the others (with a higher relative amount of Na-K and SO_4).

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Brine exploration from the geothermal complex of the Liquiñe-Ofqui fault zone as a response to power generation

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The increasing energy demand in Chile and the state policies focused on decarbonization require continuous and sustainable electricity generation methods. Geothermal energy represents a viable solution on environmental areas and cyclical production, contributing with continuous energy production. Despite the proven geothermal potential in Chile, there is a lack of geothermal production due to economic barriers, such as high implementation costs and state policies focused on other types of energy sources. The Liquiñe-Ofqui fault zone (ZFLO) between 38° and 48°S, is a system of Andean transverse faults parallel to the magmatic arc, constituting the main structural feature of the Southern Volcanic Zone of the Andes (Lavenu, A. &. 1999, *Revista Geológica de Chile*, *26* (1), 67-87); (Rosenau, M. 2006, *Tectonics*, 25, TC4013); (Sanchez, P. 2013, International Geology Review, 55:11, 1384-1400), which characterize and define a geothermal system, dominated by volcanic-structural regimes, abundant thermal waters generated by infiltration of meteoric waters and groundwater circulation (Hawkins, A. J., Tester, J.W. 2016. Encyclopedia of Geochemistry. pp 592–597), necessary conditions for geothermal systems like heat sources, high level of precipitation and existence of permeability structures for circulation of deep fluids. Demonstrating its high potential for electricity production in different areas of the system. These characteristics suggests that the geodynamic conditions of the ZFLO are conducive to the development of geothermal systems capable of generating energy and concentrating saline fluids with elements such as Li, B and/or rare earths from the circulation of deep fluids. High temperatures in principal reservoir induce chemical reactions, producing dissolution and precipitation of minerals, resulting transfer of dissolved species from the host rock to the geothermal fluid by possible cation leaching. To establish the areas where the potential for electricity generation and the potential for lithium extraction converge is the first step to remove the economic barriers that until now limit the use of geothermal resources. Taking as a case study, the ZFLO, a widely studied area in relation to geothermal potential, this research aims to propose a modernization of the industry with hybrid processes, related to electricity production associated with the exploration of brines for the extraction of Li, B and/or rare earth elements, which make profitable and encourage capital investment in geothermal energy.

Financing: Escuela de Geología. Universidad Santo Tomás

Poster Presentations

Technical Session 8

Linking geology and geochemistry to viticulture and wine / 1st IGVWS2022

Knowledge dialogues: Biodinamic agriculture and Mapuche AZ MAPU

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A more holistic approach of Terroir concept involves the people who cultivated the grapes and make the wine. In this sense, this study introduces the philosophical and practical principles of biodynamic agriculture as a strategy for soil restoration in the Nagche territory within the Malleco Valley, through the Mapuche participatory methodologies of *trawun* and the *nutram*. During the development of the workshops, the Mapuche participants compared their own traditional practices, many of them forgotten, with the principles of biodynamic agriculture (Rudolf Steiner; 1924). Activating their emotional, family, and collective memory to recount the practices transmitted to them by their parents and grandparents. Among them, the Az mapu, a set of philosophical principles that guide the relationship of the Mapuche to maintain balance with their territory, with the different human and non-human entities that inhabit it (social perspectivism), as well as with the cosmos. In the same way, the participants reported the breakdown of this order and the loss of their knowledge and language as a consequence of the processes of colonization and exclusion of the Mapuche by the hegemonic society in Chile. On the other hand, they identified both agricultural and forestry state policies as the main causes of soil depletion, erosion, as well as drought and the loss of groundwater. In this sense, they report to acquire a new conceptual tool that allows them to better translate their philosophical principles before the agents of the Chilean State responsible for both the sociocultural and territorial reconstruction of Mapuche as well as to alleviate the consequences of centuries of monocultures in their territory and the local manifestations of the global ecological crisis.

Key words: Interculturality, Malleco Valley, Soil restoration

Influencias geomorfológicas y del material parental en el terroir de un cultivo de *vitis vinifera* en Casas Viejas, Chile central (34°23’S, 71°19’O)

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Este trabajo busca entender las influencias del material parental y la geomorfología sobre las características físicas del terroir de un viñedo dentro de un valle de la Cordillera de la Costa de Chile Central.

Se realizan calicatas, descripciones geomorfológicas, litológicas, y pedológicas del suelo. Junto con análisis petrográficos y químicos por fluorescencia de rayos X (XRF) a rocas y análisis de clase textural, densidad real, densidad aparente, curva característica y química por XRF en suelos. Además, se computaron geoprocesos como radiación e insolación solar, análisis de aspecto y pendiente.

Se establece así una relación directa de la influencia del material parental sobre la formación de un horizonte argílico y la precipitación de nódulos de Fe-Mn. Por otra parte, la geomorfología genera zonas de influencia según la posición fisiográfica que ocupen los suelos, ya que los suelos formados en la zona distal del abanico aluvial o sobre el relleno aluvial del valle difieren bastantemente de los formados sobre la extensión de un cordón montañoso.

Guía Kalycatas: Deconstruyendo el Terroir

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Debido a que normalmente existe una desconexión entre la información científica referente a los componentes del Terroir y el público que consume vinos de alta gama, es que nace esta primera y única Guía Terroir del mercado vitivinícola de Chile y el extranjero. Su objetivo es de-construir y difundir cada año las características y singularidades del viñedo de origen. Y una de las áreas donde pone mayor acento es la geología. Revelar las diferencias litologías en cada denominación de origen (D.O.) del país y las disímiles geomorfologías que dan forma a los viñedos. Además de entregar información sobre las otras variables del Terroir: como son el clima, el suelo, la planta, la práctica vitícola, enológica y el equipo humano detrás. Escrita en castellano y traducida al inglés y al portugués, apunta a un público nacional e internacional consumidor de vinos de alta gama. Está en formato digital y es distribuido a todo el mundo de forma gratuita a público general, tiendas especializadas y restaurantes. Guía Terroir Kalycatas es producida por Kalycatas Producciones, laboratorio terroir enfocado en investigar (consultorías), producir contenidos (guías, libros, mapas) y difundir el terroir a través de seminarios y cursos especializados.