16TH SGA BIENNIAL MEETING
28–31 MARCH 2022

ROTORUA, NEW ZEALAND – VIRTUAL CONFERENCE

THE CRITICAL ROLE OF MINERALS IN THE CARBON-NEUTRAL FUTURE

PROCEEDINGS
VOLUME 2
The theme for this 16th edition is “The critical role of minerals in the carbon-neutral future”

Suggested citation for the entire proceedings:

Suggested citation for an individual paper:

Suggested citation for an individual abstract:

This publication cannot be reproduced in whole or in part without the permission of The Society for Geology Applied to Mineral Deposits (SGA).

A digital version of this Proceedings is available from the SGA website www.e-sga.org
CONTENTS OF VOLUME 2

Plenary keynote presentations

Pining for an anomaly: vectoring towards mineralization using biogeochemistry
Cohen DR 39

Geological evolution of the Lihir gold deposit, Papua New Guinea
Cooke DR, Lawlis E, Sykora S, Selley D 40

Orogenic gold mining and exploration in the Otago Schist, New Zealand
Craw D 41

Submarine hydrothermal systems as the shallow parts of porphyry Cu systems: the case for Brothers volcano
de Ronde CEJ, IODP Expedition 376 Scientists 44

Trace element deportment – knowledge is power
Escolme A 53

Estimation of gangue mineral percentages from routine drill hole analyses
Halley S 70

Gravity Recovery of Gold - Past, Present and Future
McGrath T 115

Resourcing a low emissions future through mineral discovery and responsible recovery
Occhipinti S 130

The critical importance of ‘secondary prospectivity’ in a dynamic global climate
Parbhakar-Fox A 133

Inherited structures and golden triggers: controls on the localization of Cretaceous-to-Recent gold deposits, Aotearoa New Zealand
Rowland JV 156

Mineral zonation and at the Ernest Henry IOCG deposit - new insights of ore formation by the integration of mineralogy, geochemistry and petrophysical data

Advances in the understanding of epithermal ore forming processes from studies of modern environments in the Taupō Volcanic Zone
Simmons SF 169

Epithermal deposits of the Hauraki Goldfield, Aotearoa New Zealand
Simpson MP, Christie AB 171
## Concurrent session presentations

**Theme: Mineral resources for the carbon neutral economy**

**Sub-theme: Critical metals including rare earth elements (REE)**

### Peralkaline and carbonatite magmatism and related critical metal mineralization

1. REE mineralization style in carbonates determined by wallrock interaction
   - *Anenburg M*

2. Carbonatite melt as a travel agent for magmatic sulfide liquid: nature vs experiments
   - *Cherdantseva M, Fiorentini M, Anenburg M, Mavrogenes J*

3. Crystallization sequence of a REE-rich carbonate melt: an experimental approach
   - *Mollé V, Gaillard F, Nabil Z, Di Carlo I, Erdmann S, Tuduri J*

4. One meter core! Detailed insight into the Storkwitz carbonatite diatreme, Germany, by μ-EDXRF based automated mineralogy
   - *Rammlmair D, Goericke D, Lapp M*

5. Application of stable isotopes to constrain rare earth element enrichment in carbonatites
   - *Verplanck PL, Johnson CA, Pribil MJ, Lowers HA*

### Critical metals and base-metal ore deposits: discovery to recovery

6. Distribution and existing forms of gallium, germanium and indium in sphalerite from Fankou lead-zinc deposit in Guangdong province, China: an ICP-MS study

7. Tellurium nanoparticle formation as evidence of tellurium biogeochemical cycling

8. Critical metals in sulfides of the Tisová Cu (Fe-As) deposit (Bohemian Massif, Czech Republic): results from LA-ICPMS study
   - *Pašava J, Andronikova I, Veselovský F, Vymazalová A, Pour O*

### Unconventional sources of critical metals

9. Using Life Cycle Analysis thinking to assess how we facilitate the mining of critical elements as by-products
   - *Clarke R, Smith D, Holwell DA, Mann S, Naden J*

10. Critical elements in fluids of the Taupō Volcanic Zone
    - *Reyes A*

11. Iron oxide-apatite (IOA) deposits as potential vanadium sources

---

vii
Enrichment mechanisms and processes of critical metal deposits

LA-ICP-MS mapping of sandstone from the Proterozoic Athabasca Basin (Canada) – implications for REE and unconformity-related U mineralization
Chi G, Potter E, Petts D, Jackson S, Chu H

Spodumene pegmatites: linked crystallization and fluid expulsion, and their implications for ore formation
Kaeter D, Menuge JF, Barros R

Lithium and boron geochemistry of melt inclusions from rhyolites parental to lithium-bearing salars of Nevada, USA and Southern Puna Plateau, Argentina
Khoury RM, Mercer CN, Hofstra AH, Roberge J

Critical elements from the Tapolcsány Formation (Uppony Mts, NE-Hungary)
Leskóné Majoros L, Szakáll S, Kristály F

Geochemistry and ore-forming processes of multistage granitic magmatism in the Central Iberian Zone: Segura-Panasqueira Belt (Portugal) case study
Martins I, Mateus A, Ribeiro da Costa I, Gaspar M, Dias da Silva I

Subvolcanic P-T phase equilibria of H₂O-CO₂-fluid saturated, Be-U-Li-F-enriched topaz rhyolite from Spor Mountain, Utah
Mercer CN, Hofstra AH

Textural and geochemical characterization of Bangombe and Bignomi manganese ore deposit in the francevillian series, Gabon: insights for better exploration and exploitation strategies

Giant Co-Ni arsenide mineralization resulting from cold hydrocarbon seep and Upper Devonian brine circulation in Neoproterozoic serpentinite (Bou Azzer, Morocco)
Saintilan NJ, Bernasconi SM, Ikenne M, Allaz JM, Souhassou M, Karfal A, Maacha L, Spangenberg JE

Theme: Specific mineral systems
Sub-theme: Hydrothermal

Intermediate and low sulfidation epithermal deposits and geothermal systems

Listwanite-hosted epithermal gold mineralization in an island arc: insights from the Malabeg Prospect, Cabangan, Zambales, Philippines
Fungo JES, Gabo-Ratio JA, Yonezu K, Jabagat KD, Barrientos MAJ, Ito K

Application of chlorite geothermometry to the Hishikari gold mine, Japan: implication for the upflow zone in the low-sulfidation epithermal system
Ammonium associated with the Favona epithermal gold deposit in the Coromandel Peninsula, New Zealand: its distribution and source
Kristoffersen NK, Hattori K, Simpson MP

Hydrothermal minerals in epithermal deposits and geothermal systems, New Zealand: the connection
Simpson MP

Hot spring deposits and epithermal environments

Jurassic shallow epithermal systems from southern Patagonia, Argentina
Guido DM, Campbell K

Delineating geothermal upflow from surface features: a Waiotapu case study
Hamilton A, Campbell K, Guido D, Dobson M, Having J, Hamilton T, Penrose L, Drake B, Rowe M

Textures and mineralogy of the Ohakuri fossilised hot spring sinter, Taupō Volcanic Zone, New Zealand
Lyon B, Campbell K, Rowe M, Hamilton A

Subaerial hot springs and near-surface hydrothermal mineral systems past and present, and possible extraterrestrial analogues
Pirajno F

Porphyry and high sulfidation epithermal deposits

Discrimination of magmatic-hydrothermal events using quartz texture and mineral chemistry
Baker MJ, Thompson J, Zhang L

Lifetime of the magmatic system and porphyry dike emplacement in the Yerington district, Nevada, USA: is it a matter of time?
Castellanos Melendez MP, Chelle-Michou C

$ or $$$? Estimating the size of porphyry Cu deposits early on Chelle-Michou C, Rottier B

Post-subduction metallogenesis in upper crustal Au-Te deposits: insights from Tuvatu, Fiji
Clarke R, Smith D, Holwell DA, Mann S, Naden J

Lithospheric architecture of the central Andes and the localization of giant porphyry copper deposits during key geodynamic epochs
Farrar A, Cooke DR, Cracknell MJ, Hronsky J, Piquer J

Alkalic Au-Cu deposits of the Cadia Valley (New South Wales) and Red Chris (British Columbia): unconventional ancient porphyry deposits associated with post-subduction magmatism
Harris AC, Fitzpatrick N, MacCorquodale F, Wilson AJ, Cooke DR, Tosdal RM

Geochronology of porphyry-style hydrothermal mineralization and alteration at Anabama Hill, Delamerian Orogen, South Australia: new insights from zircon U-Pb, molybdenite Re-Os and white mica Rb-Sr ages
Hong W, Fabris A, Wise T, Dutch R, Gilbert S
Host-rock driven compositional and morphological differences in porphyry Cu-Au systems: examples from the Northparkes district, NSW, Australia

Hoye J

The significance of phyllic alteration at the E26 porphyry Cu-Au deposit, Northparkes, NSW, Australia

Jones R, Cooke DR, Zhang L, Escolme A, Hoye J

Cu-Au porphyry fertility of Lachlan Orogen intrusions - insights from apatite inclusions in zircon

Kendall-Langley LA, Kemp AIS, Hawkesworth CJ, Roberts MP

Sources of sulfur in the Erdaohezi Pb-Zn-Ag deposit, NE China: constrains from in-situ sulfur isotope analyses

Liu Y, Moritz R, Bouvier A-S

What does the geochronology of supergene alteration and Cu-enrichment tell us about the landscape evolution in the Atacama Desert?

Morales-Leal J, Campos E, Riquelme R, Salazar J, Spiking R

Cu-Ag-Pb mineralization of Agdim - Ait El Fersi sector, northeastern part of the Moroccan Anti Atlas belt: geological, mineralogical and geochemical characteristics


The Santo Tomás project, Sinaloa and Chihuahua, México: a particularly elongated porphyry copper deposit

Pelletier J, Quintana M, Caiza EK, McGuigan P, Chavez WX Jr

The new epithermal gold deposits within the Okhotsk-Chukotka Volcanic Belt, north-east of Russia

Pilitsyna (Pavlova) TA, Pilitsyn AG, Volkov AV

Experimental modeling of Cu and Ag coupled transport by chloride hydrothermal fluids at 350–450°C and 1000 bar

Rubtsova EA, Tagirov BR, Nikolaeva IY, Tarnopolskaya ME

Aluminium phosphate-sulfate (APS) minerals: a new potential exploration tool in porphyry – high-sulfidation epithermal deposits

Seow XN, Zhang L

Halogen and sulfur evolution from apatite in porphyry-like volcanic systems, West Luzon Arc, Philippines

Stonadge G, Miles A, Knott T, Smith D, Large S

Accessory minerals: a window into Cu “fertility” in post-subduction magmas in the Aegean

Tuffield L

Iron oxide copper gold (IOCG) deposits

Unveiling the polyphasic evolution of the IOCG Salobo deposit, Carajás Mineral Province, Brazil: insights from magnetite trace elements and sulfur isotopes

Campo Rodriguez YT, Schutesky Della Giustina, de Oliveira CG, Whitehouse MJ
Gold in metamorphic terranes — new research approaches, new models and new target areas

Comparative study of the greenstone and granitoid hosting orogenic gold in the Bétaré Oya and Colomine districts, eastern Cameroon: an overview
Azeuda Ndonfack KI, Xie Y, Goldfarb RJ, Zhong R

Genesis of gold mineralization in the Pahardiha-Rungikocha gold deposit, North Singhbhum Mobile Belt, eastern India: a geochemical and mineral-chemical approach
Barla A, Singh S, Chakravarti R

Rheological controls on gold mineralization and ore shoot geometry: an example from the Oberon orogenic gold deposit, Tanami, Northern Territory, Australia
Crawford A, Thébaud N, Masurel Q

Fracture-hosted Fe-Hg mineralization in the Orihuela dolerite, Betic Cordillera, SE Spain
González-Jiménez JM, Ferreira-García AR, Blanco-Quintero IF, López-García M, Cañaveras JC, Piña R, Corral I

New insights into the Neoarchean geological evolution of the Yilgarn Craton and implications for gold explorers
Masurel Q, Thébaud N

Revelations through micro-characterization of komatiite-associated invisible Au
McFarlane HB, Hu S, Godel B, Pearce M, Dugdale A, Clifford J

Crustal-scale transport of nanoparticle forms ore deposits
Petrella L, Thébaud N, Fougerouse D, Martin L, Suvorova A, Turner S, Gain S

Integrated geochemical, sedimentological and structural interpretation of the Palaeoproterozoic Granites-Tanami Orogen – vectoring towards gold mineralization
Schmid S, McFarlane H, Blaikie T, Kunzmann M

Characterization of gold mineralization at the Tau orebody, Mupane, Botswana
Seaba O, Imai A, Baliki K

Contribution of remote sensing and geophysics to the exploration of a gold site: case of Iskel indices (Western Hoggar, Saharan desert), preliminary results
Seray N, Menasria HG, Latreche A, Chaouche I
Stratigraphy, hydrothermal alteration and geochemical signature of Faina gold deposit, Pitangui Greenstone Belt, Brazil
Silva G, Neto AVC, Alves FE, Sampaio P, Soares MB, Silveira VD

Controls on high-grade versus refractory mineralization in Archean orogenic gold systems
Sumail, Thébaud N, Masurel Q, Petrella L

Function and status of structural geology in resource management
Vearncombe JR

Inheritance of trans-lithospheric structures and fossil ore-fertile mantle source domains at long-lived supercontinent margins
Wiemer D, Hagemann SG, Kemp AIS, Thébaud N, Martin L, Hronsky J, Ireland T, Villanes C

**VMS systems: modern and ancient**

Lithospheric-scale structural controls on seafloor massive sulfide deposits in the Mariana subduction zone

_Acuña-Avendaño O, Anderson M_

Hydrothermal versus protolith compositional controls on the metal endowment of VMS deposits in proto-arc terranes

_Belgrano TM, Milton JA, Teagle DAH, Diamond LW_

Permeability available for hydrothermal leaching of VMS metals from basaltic lavas: Semail ophiolite, Oman

_Brett AC, Diamond LW_

Ore-bearing fluids for VMS deposits in basaltic oceanic crust: insights from the Semail ophiolite, Oman

_Diamond LW, Richter L, Pettke T_

The origin of pyrite-sphalerite banding in metamorphosed volcanogenic massive sulfide deposits

_Dudley B, Brueckner SM_

Magma fertility in Brothers submarine volcano

_Georgatou A, de Ronde CEJ_

Evaluating hydrothermal episodicity and rates of ore-forming processes at the seafloor

_Jamieson JW, Galley CG, McNeil NC, Sánchez Mora D, Maccali JM, Roerdink DL_

Expanding the Au-Ag hybrid VMS model to include high sulfidation deposits

_Lefebure DV_

Metal distribution in the gossans of Lagoa Salgada, Caveira, Lousal, Montinho, Aljustrel, São Domingos and Chança VMS deposits, Iberian Pyrite Belt, Portugal

_Matos JX, Batista MJ, Silva TP, de Oliveira DPS, Relvas JMRS, Barriga FJAS_

Replacement or plume fallout? Both, please! Evidence from active and fossil VMS systems

_Relvas JMRS, Barriga FJAS, Pinto AMM, Marques F, Carvalho J, Dias A_
The Geodynamic controls on modern seafloor massive sulfide deposition: a remote-predictive mapping approach
Summer D, Anderson M

Source rocks for metals in basalt-hosted VMS deposits: Semail ophiolite, Oman
Wolf RC, Diamond LW, Pettke T, Belgrano TM

Deciphering thallium deportment and remobilization in shallow-water massive sulfides at the Kolumbo arc-volcano, Greece: evidence from in situ LA-ICP-MS study and thallium-isotope fractionation

Distal signatures and vectors toward mineralization in carbonate rocks: porphyry, skarn, vein and replacement deposits

Indium mineralization from Zlatý Kopec skarn deposit: complex metallogeny of Fe – Sn – polymetallic skarn-hosted mineralization in Krušné hory/Erzgebirge Mts
Bohdalek P, Pour O, Andronikova I

Hydrothermal signatures in Lower Carboniferous carbonates in the Irish orefield: recent geological and geochemical advances in understanding ore genesis and providing exploration vectors
Burton E, Doran A, Zhou L, Torremans K, Menuge J, Hollis SP, Yesares L, Güven J, Hitzman M

Sulfur content in calcite measured using LA-ICP-MS/MS and its application in mineral exploration
Chang Z, Huang S, Kirschbaum M

Mineralizing fluids in the Catalina Huanca carbonate-replacement Zn-Pb-Ag deposit, southern Peru
Espinel Pachon IM, de Haller A, Kouzmanov K, Tollan P, Spangenberg JE

Distal signatures of the Bingham porphyry Cu-Au-Mo mineralization in carbonate wallrocks

Evolution of the Ertsberg pluton, Ertsberg-Grasberg mining district, Papua, Indonesia
Makis J, Cloos M

Manganese-based vectoring in distal carbonate replacement deposits
Megaw PKM, Hansen LD, Lambeck L, McGlasson JA, Jensen CG

Characterizing the mineralogical and geochemical halo of the giant Mt Isa Pb-Zn-Ag-Cu deposit using integrated hyperspectral and X-ray fluorescence (XRF) core scanning technology
Parchegani A, Fox N, Gow P, Valenta R

Geochemical zoning patterns in carbonate wallrocks of the Candelaria Cu-Au district, Chile
Piurkowsky S, Chang Z, Brunetto P

3D geological model of the Dolphin tungsten skarn deposit, King Island, Australia
Roach MJ, Zhang L, Cooke DR, Testa F, Callaghan T
Using visible-near, shortwave and thermal infrared spectral data, and mineral chemistry to aid tungsten skarn exploration: a case study from the Dolphin Deposit, King Island, Australia
Zhang L, Testa F, Cooke DR, Moltzen J, Goemann K, Feig S, Callaghan T

Sediment hosted zinc-lead deposits

Geology and genesis of the giant Gorevskoe Pb-Zn-Ag deposit, Krasnoyarsk Territory, Russia
Belokonov G, Frenzel M, Priyatkin N, Renno AD, Makarov V, Gutzmer J

Tracking the temperature and composition of hydrothermal fluids: the application of clumped O-C and strontium isotope analyses in the Irish Zn-Pb orefield
Doran A, Menuge J, Hollis S

Spatial controls, mineralogical variation and paragenetic sequence of the mineralization and alteration at the Rosh Pinah Zn-Pb deposit, Namibia

Ore-forming conditions at the Gorno MVT district, Lombardy, Italy
Giorno M, Bertok C, Martire L, Barale L, Burisch M, Frenzel M, Looser N, Bernasconi SM

3D geological modeling of the Black Angel Zn-Pb mine area (Maarmorilik, West-Greenland) and its implications for mineral exploration

Characterizing the spatial distribution of regional and hydrothermal dolomitisation along the Rathdowney trend, Ireland: implications for base metal exploration
Vafeas NA, Hitzman M, Güven J, Torremans K

Sediment hosted copper deposits

Linking complex vein paragenesis with kyanite growth and copper sulfide mineralization at low temperatures in the Congolese Copperbelt
Bidgood AK, Hitzman M, Twigg H, Johnson S, Chew D

Mafic rocks as a source of Cu, Co and Ni in the Central African Copperbelt
Holwell DA, Blanks D, Phelps-Barber Z, Kaemba R

Constraining Cu-Co mineralization in the Zambian Copperbelt using accessory minerals: rutile, apatite and monazite

Sediment hosted Carlin gold and other types of deposits

Diagenetic constraints on the formation and replacement of bedded barite in the Selwyn Basin, Canada
Grema HM, Magnall JM, Whitehouse MJ, Gleeson SA, Schulz H-M
A novel method of age constraint on Mississippi Valley-type Pb-Zn deposits by palynomorphs: a case study of the Changdong deposit in China
Liu Y

A new genetic model for marine ooidal iron ore deposits in Western Siberia, Russia
Rudmin M

New insights into origin of Oligocene channel ironstone deposits in Turgay depression
Rudmin M

Genesis of the Gongchangling BIF-related high-grade magnetite ore in the Anshan-Benxi area, North China Craton
Sun X, Luan Y

**Antimony and related elements mineralization: magmatism, fluids and sediments**

Mafic magmatism and Sb mineralization: geochemical insights from the Central Iberian Zone, Spain

Gravimetric survey in the Alto do Sobrido and Ribeiro da Serra mines, Portugal
Carvalho A, Ribeiro R, Lima A, Moura R, Gloaguen E

Geochemistry of antimony mineralizations in La Balanzona and Accesos mines, Central Iberian Zone, Spain

Antimony mineralizations in the Guadalmez syncline – relationships with Almadén mercury deposits, South-Central Spain
Higuera P, Lorenzo S, Maria Esbri J, Campos Rodriguez H, Gloaguen E

Determination of the processes behind Sb, As and W enrichment in magmas using geochemical databases
Mollé V, Iacono-Marziano G, Campos Rodríguez H, Gloaguen E, Tuduri J, Pochon A

Toward a better understanding of Sb metallogeny in the Variscan belt

Antimony mineralization: the Archaean Murchison Belt, South Africa
Vearncombe JR

Metallogeny of Sb along the Ibero-Armorican Arc: insight from data-driven prospective mapping
Vella A, Bertrand G, Toulière B, Gloaguen E, Labbé V, Gumiaux C, Sizaret S

**Uranium mineral systems and exploration methods**

Post-magmatic alteration of uranium mineralization in the Damara Orogen
Otto A
Mineral systems model for surficial uranium deposits

Wilde A

Towards a mineral systems model for leucogranite-hosted uranium deposits

Wilde A

**Sub-theme: Magmatic mineral systems**

**Metallogenic processes within mafic-ultramafic magmatic systems**

Nickel depletion and enrichment in olivine in mafic-hosted Ni-Cu sulfide systems

*Barnes SJ, Yao Z-S, Mao Y-J, Jesus AP*

The origin of Cu-(Te-Au-Ni-PGE) sulfide deposits of the Curaçá Valley, Brazil: can tellurium settle the genetic debate?

*Blanks D, Holwell DA, Thompson J, Mota I, Porto F*

Chromitite-associated PGE-(Ni-Cu) mineralization in the Lower Zone of the northern Bushveld: new insights from Zwartfontein

*Canham K, Holwell DA, McDonald I, Lloyd A*

Olivines and Cr-spinels from the Noril’sk-1 deposit: compositional features and petrological implications

*Chayka IF, Kamenetsky VS, Izokh AE, Kalugin VM, Zhitova LM, Gora MP, Shevkov AA, Shvedov GI*

Evolution of the Ni-Cu-PGE ore system in the middle part of the Norilsk 1 intrusion: insights into the single vs multiple magma pulses model

*Garcia JA, Tolstykh ND, Shvedov G*

The critical role of magma degassing in sulfide melt mobility and metal enrichment


Study of magmatic sulfide melt infiltration into an unconsolidated silicate mush - analogue modeling

*Le Vaillant M, Barnes SJ, Slim A, Coward A, Maksimenko A*

Ni-PGE enrichment on the Vermelhos Cu deposit, Curaçá Valley district, Brazil


Mesoscopic aspects of chromitite from UG2, Bushveld Complex, South Africa

*Rammlmair D, Meima J, Goericke D, Nikonow W*

Formation of the titanomagnetite deposit in Yeoncheon, South Korea

*Seo J, Choi S-G, Lee YJ*

Magmatic stratigraphy of the Platreef at Tweefontein, northern limb of the Bushveld Complex

*Thompson ES, Holwell DA, Lloyd A*

Textural characterization of the Fe-Ti oxides from the Tete Suite, Mozambique

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magmatic and hydrothermal deposits related to felsic rocks</td>
<td>64</td>
</tr>
<tr>
<td>Portuguese Variscan granites with metallogenic potential: what are</td>
<td></td>
</tr>
<tr>
<td>their geological, petrophysical and geochemical signatures?</td>
<td></td>
</tr>
<tr>
<td>Gonçalves A, Sant’Ovaia H, Noronha F</td>
<td></td>
</tr>
<tr>
<td>Hypogenic mineralizations of W and Sn in Northern and</td>
<td>122</td>
</tr>
<tr>
<td>Central Portugal, and Castille and León regions of Spain</td>
<td></td>
</tr>
<tr>
<td>Mota A, Noronha F</td>
<td></td>
</tr>
<tr>
<td><strong>Sub-theme: Placer deposits</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Placer deposits</strong></td>
<td></td>
</tr>
<tr>
<td>Placer gold morphology, composition and concentration during</td>
<td>42</td>
</tr>
<tr>
<td>extensive recycling, southern New Zealand</td>
<td></td>
</tr>
<tr>
<td>Craw D</td>
<td></td>
</tr>
<tr>
<td>A zircon perspective on the upgrading of heavy mineral sand placer</td>
<td>48</td>
</tr>
<tr>
<td>deposits</td>
<td></td>
</tr>
<tr>
<td>Dröllner M, Barham M, Kirkland CL</td>
<td></td>
</tr>
<tr>
<td><strong>Sub-theme: Regional</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Metallogeny of Central Tethyan Belt</strong></td>
<td></td>
</tr>
<tr>
<td>Mineral potential mapping by using a cell-based association approach,</td>
<td>83</td>
</tr>
<tr>
<td>a case study from Kajan area, Iran</td>
<td></td>
</tr>
<tr>
<td>Irani Z, Asadi Haroni P, Mohammadi H</td>
<td></td>
</tr>
<tr>
<td>External controls in metal endowment and styles of mineralization in</td>
<td>96</td>
</tr>
<tr>
<td>andesitic volcanoes – example from the Štiavnica stratovolcano,</td>
<td></td>
</tr>
<tr>
<td>Slovakia</td>
<td></td>
</tr>
<tr>
<td>Arc magmatism and metallogeny in the Lesser Caucasus and Eastern</td>
<td>151</td>
</tr>
<tr>
<td>Pontides: geochronology, geochemistry and geodynamic implications</td>
<td></td>
</tr>
<tr>
<td>Rezeau H, Hässig M, Moritz R, Chiaradia M, Sadikhov E</td>
<td></td>
</tr>
<tr>
<td>Epithermal systems in the Bolnisi district, Georgia and the Artvin</td>
<td>172</td>
</tr>
<tr>
<td>district, Turkey: fundamental features of alteration, ore-style and</td>
<td></td>
</tr>
<tr>
<td>ore-forming patterns</td>
<td></td>
</tr>
<tr>
<td>Sonmez SU, Moritz R, Golay T, Gialli S, Turlin F, Lavoie J,</td>
<td></td>
</tr>
<tr>
<td>Popkhadze N, Natsvlishvili M, Aydin U, Keskin S</td>
<td></td>
</tr>
<tr>
<td><strong>New Zealand mineral deposits and metallogenesis</strong></td>
<td></td>
</tr>
<tr>
<td>Magmas, metals and deep roots of geothermal systems in the Taupô</td>
<td>30</td>
</tr>
<tr>
<td>Volcanic Zone, New Zealand</td>
<td></td>
</tr>
<tr>
<td>Chambefort I, Dilles J</td>
<td></td>
</tr>
<tr>
<td>Exploration history of the Wharekirauponga low-sulfidation epithermal</td>
<td>61</td>
</tr>
<tr>
<td>Au-Ag deposit, Hauraki Goldfield, Coromandel, New Zealand</td>
<td></td>
</tr>
<tr>
<td>Gardner T, Torckler L</td>
<td></td>
</tr>
</tbody>
</table>
The influence of host rocks on epithermal veining in the Waihi area of New Zealand

Richards S, Torckler L

Theme: Ore-forming processes

Ore-forming processes and regional settings, including pegmatite-related critical metal deposits

Heavy rare earth elements potential of the Entia Pegmatite Field, Central Australia

Cenki B, Nollo J, Parat F, Rey PF

Geology of the Lubambe Cu-Co deposit, Zambia: lithofacies and geochemistry of the Neoproterozoic metasedimentary succession

Doran A, Torremans K, Hitzman M, Stacey J

Metallogenic processes of the Tongchang Cu-Fe deposit: constraints from the in-situ S isotopes

Luan Y, Sun X

The Massif 1 of the Bakwanga Kimberlite field: facies and diamond potential (Kasai craton, D.R. Congo)

Mukonki P, Mumba C, Batumike J, Mambwe P

Metamorphic evolution and metallogenic value of the Tokmovo megablock and its tectonic position in the Volgo-Uralia segment, East European Craton

Pavlova TA, Samsonov AV

Mineral prospectivity of a lithium-bearing pegmatite, in northern Portugal

Tucker Vasques J, Lima A, Ribeiro MA

Theme: Geometallurgy

Complex orebodies - unlocking future resources through orebody knowledge and geometallurgy

Beyond conventional geometallurgy: a broader view to be prepared for a circular economy

Baumgartner R

Thermal infrared-active vibrational modes of spodumene and their relationship to Fe-content

Laukamp C, LeGras M, Pejcic B

Towards unlocking the value of detailed characterization data for comminution and geometallurgical modeling

Lois-Morales P, Evans C, Weatherley D

Quantitative image textural analysis for copper flotation recovery

Merrill-Cifuentes J, Cracknell MJ, Escolme A
Theme: New research and exploration developments

Spatial data analysis for mineral exploration

3D geological–geophysical–geochemical modeling of the Russell Lake property (Saskatchewan, Canada): targeting/discovering basement-hosted uranium deposits
Bravo JA, Annesley IR, Hajnal Z, Bauer T

Stochastic uncertainties due to training deposits for data-driven mapping of mineral potential: challenges and a proposed solution
Carranza EJM, Parsa M

PRISMA hyperspectral remote sensing for exploration of Co-Ni deposits: example from the Punta Corna cobalt project (Piedmont, Italy)

Mapping Pb isotope variations across Ireland: from regional metallogeny to deposit-scale fluid flow
Hollis SP, Doran AL, Menuge JF, van Acken D, Daly SS, Piercey SJ, Cooper MR, Unitt R, Turner O

Using multidimensional mineral systems-based predictive models to tackle the growth challenge facing the mining industry
Januszczak N

Geological distance
Jessell M, Ogarko V, Kelka U, Pirot G, Lindsay MD

3D geophysical-geological modeling of the Needle Falls Shear Zone (Saskatchewan, Canada): structural/tectonic controls on base metal mineralization
Murhula EM, Annesley IR, Hajnal Z

Cobalt prospectivity in Finland
Nykänen V, Niiranen T, Törmänen T

2D mineral predictive mapping with machine learning algorithms in Colombia
Pizano LA, Barth A

Application of spatial point pattern analysis of porphyry copper deposits in Kerman Belt, southeastern Iran
Sadigh S, Mirmohammadi M, Asghari O, Porwal A

Coupling Disc-Based Association and Random Forest for prospectivity mapping
Vella A, Bertrand G, Tourlière B, Gloaguen E, Labbé V, Gumiaux C, Sizaret S

Multivariate geochemical analysis applied to mineral exploration in Andean-type tectonic setting
Verbel Olarte AA, Schutesky ME, Gregory DD
# Data-driven geoscience: machine learning and multivariate data analysis

Machine Learning for automated detection of geophysical features associated with carbonatites and alkaline ring complexes
*Aranha M, Porwal A*

Trace element composition of chalcopyrite as a tool for deposit type recognition: a machine learning approach
*Caraballo E, Beaudoin G, Dare S*

Machine learning applied to mineral deposits
*Hood S*

Geological modeling using MWD data
*Karlson L, Keep M, Jessell M, Pirot G, Lindsay M, Karlson L, Minniakhmetov I*

New applications of hyperspectral sensing for geological exploration using multivariate statistical methods
*Kereszturi G, Chakraborty R, Rodriguez-Gomez C*

Generating multiscale, multivariate geology logs from hyperspectral outputs
*Stromberg J, Hill J*

Modeling deleterious elements with “less than one” datasets via deep learning methods and non-linear correlation studies
*Yusufali F, Sucholutsky I*

# Mineral vectors towards ore deposits: advances, applications and novel methods

Translating lithogeochemistry into petrophysics: vectoring to IOCG mineralization undercover
*Austin AR, Schlegel TU, Birchall R, Patterson B, Bjork A, Walshe J, McFarlane H, Stromberg J, Pearce M*

The Potassium Mobility Index (KMI): an XRF-appropriate discriminator for sericitic and chloritic alteration
*Bamforth T, Hu S, González-Alvarez I*

Hydrothermal wall rock alteration related to Late Variscan Pb-Zn-Ag-(Au) mineralization and its implication for exploration in the Freiberg District, Germany
*Birtel S, Gutzmer J*

Zircon as an exploration tool for iron-oxide copper-gold mineralization
*Brotodewo A, Tiddy C, Giles D, Zivak D, Fabris A, Light S, Forster B*

Geology and mineral chemistry of alteration minerals at the Mt Eliott, Corbould and SWAN deposits, NW Queensland, Australia
*Cloutier J, Steadman J, Hohl M, Cooke DR, Barker SLL*

LocatOre: a tool for modeling proximitor equations using multi-element mineral chemistry data
Alteration footprints of the Vulcan IOCG prospect, South Australia: insights from HyLogger-3 mineralogy

Dmitrijeva M, Huntington J

Updating brownfield areas with modern techniques: use of portable X-ray diffraction and hyperspectral SWIR analysis for systematic alteration mineralogy mapping at the VMS-type Aijala-Metsämonttu deposit in southwestern Finland

Huovinen I, Siira J, Kuikka J

Using scheelite composition and statistical analysis to distinguish ore deposits

Miranda ACR, Beaudoin G, Rottier B

Automated mineralogy applied to a poly-metamorphic terrain: an example from the Archean Vumba Schist Belt, Botswana

Rammlmair D, Göericke D

Tracking the Ernest Henry signature: insights from epidote and chlorite chemistry

Steadman J

Monazite as an exploration tool for iron oxide-copper-gold mineralization

Tiddy C, Giles D, Brotodewo A, Zivak D, Hill J, Hodgkinson J, Neumann M

Geochemical anomaly classification and modeling in mineral exploration

An improved generative adversarial network for mapping geochemical anomalies

Farahbakhsh E, Sadeghi B, Müller RD, Chandra R

Soil sampling campaign and geochemical analysis in the Ribeiro da Serra Sb-Au mine (Gondomar, Portugal)

Frutuoso R, Lima A, Soares F, Carvalho A, Ribeiro M

Alternatives for geochemical modeling in time and space

Lindsay M, Occhipinti S, Metelka V

Compositional MAF and geostatistical analysis of geochemical data to reveal geochemical anomalies for natural resource estimation

McKinley JM, Mueller U, Grunsky E, Scanlon R, Cooper M

Deep time exploration

Müller RD

Mineral exploration in weathered and covered terrains

Experimental estimation of carbon dioxide emissions by laterite rocks

Iunusova MM, Vorobyev SA, Makarova MA

Size matters: why smaller soil particle sizes improve exploration geochemistry through cover

Improving precious metal detection in groundwater: a comparison of sorbents

_Plet C, Reid N, Godel B, Noble R_

Indicator minerals and geochemical footprints in cover
over the Nova-Bollinger Ni-Cu-Co sulfides, Western Australia

_Salama W, Thorne RL, Anand R, Davis A_

**Trace elements in minerals: where do we stand on the road between the holy grail and a can of worms?**

Feldspar and muscovite chemistry from Be-Nb-Ta mineralized Yamrang Pegmatite, Eastern Nepal Himalaya

_Bhandari S, Qin K_

Lessons from the self-organization concept for geological and ore forming processes

_Dietrich S_

Developing trace elements in pyrite as a petrogenetic discriminant tool for gold mineralization: example from the Abitibi greenstone belt, Canada

_Genna D, Gaboury D, Dare S, Azevedo C, Jébrak M_

Trace element systematics of magnetite from the Starra IOCG system, NW Queensland, Australia

_Hohl M, Steadman JA, Cloutier J, Cooke DR, Barker SLL_

Trace elements in apatite record differentiation processes in Sept-Iles mafic layered intrusion

_Kieffer MA, Dare SAS, Namur O_

New mapping protocol using a rapid response cell (fast-funnel) for laser ablation coupled to a time-of-flight mass spectrometer (LA-FF-ICP-TOF-MS) for the fast, simultaneous quantification of multiple minerals

_Savard D, Bédard P, Dare S, Barnes S-J, Petrus J, Shelley M, Norris A_

The state of Cu, Ag and In in sphalerite determined by X-ray absorption spectroscopy of synthetic crystals and theoretical modeling

_Trofimov ND, Nickolsky MS, Filimonova ON, Evstigneeva PV, Tagirov BR, Trigub AL, Chareev DA Kvashnina KO_,

**Theme: Sustainable mining, environment, and social performance and acceptance**

**From sustainable mining to sustainable mining regions**

Hybridization of mines in Africa through a reform of legal regimes and statutes on renewable energies

_Bidjo mbonomo MV_

(Dis)connecting spaces and stakeholders: lithium materialities in Australia and Latin America

_Bos V, Forget M, Carballo AE, Gunzburger Y_

The mining company in New Caledonia: relying on the customary Kanak network to sustain nickel extraction?

_Boudjema V_
### Secondary prospectivity of mine waste: from metals to construction materials

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application of a geochemical-mineralogical approach to sulfidic tailings from Neves Corvo mine, as indicator for future mining and remediation</td>
<td>52</td>
</tr>
<tr>
<td>Gomez Escobar A, Relvas JMRS, Pinto AMM, Oliveira M</td>
<td></td>
</tr>
<tr>
<td>Critical metal mobility and recovery from weathered serpentinite and serpentinite skarn tailings from Lord Brassey Mine, Australia and Record Ridge, British Columbia, Canada</td>
<td>76</td>
</tr>
<tr>
<td>Determination of rare earth element content in mine waste, Phosphate Hill mine, NW Queensland</td>
<td>84</td>
</tr>
<tr>
<td>Jackson L, Parbhakar-Fox A, Degeling H</td>
<td></td>
</tr>
<tr>
<td>Joining the geochemical rocks: mapping the potential of mine tailings and waste rock in Australia</td>
<td>122</td>
</tr>
<tr>
<td>Mudd GM</td>
<td></td>
</tr>
</tbody>
</table>
Exploring the potential for critical metal resources in mine waste: geometallurgical characterization of cobalt-bearing minerals in tailings at the Capricorn Copper Mine, Northwest Queensland


Opportunities for valorisation of spent heap leach materials- examples from Northwest Queensland, Australia

Parbhakar-Fox A, Jackson L, Degeling H

Critical metals concentration from wastes mines in Mexico, Chile and Australia: a data integration approach

Sáez-Salgado E, Villa Gomez D, Mejías O, Parbhakar-Fox A, Pinedo-Torres LA, Jackson L, Pat-Espadas AM

Expanding the perspective on mine waste value with an emphasis on critical minerals and environmental mitigation

Seal RR II, Piatak NM, White SJO, Hayes SM

Development geosciences and mineral resources for society

The West African Exploration Initiative (WAXI): 15 years of research for development

Jessell M, The WAXI Team

The Agate Project

Thébaud N, Jessell M, Debat C, Siebenaller L

Theme: Diversity and inclusion

Diversity and inclusion

Dance parties in geosciences

Tiddy C, Perera S, Sardeshmukh S
Lithospheric-scale structural controls on seafloor massive sulfide deposits in the Mariana subduction zone

Octavio Acuña-Avendaño, Melissa O. Anderson
Department of Earth Sciences, University of Toronto, Toronto, Ontario, Canada

Seafloor massive sulfide deposits (SMS) is a term used to describe relatively young hydrothermal systems currently forming massive sulfide deposits analogous to ancient VMS deposits found on land. One of the significant differences between SMS and VMS is that the former tend to be small and have low tonnage. This has raised the question of where, if at all possible, a large SMS comparable to the large VMS known on land could be found in modern oceans. A heat source and permeability are fundamental factors for the occurrence of a hydrothermal system. Other factors such as lithospheric scale structures may be crucial to the occurrence of an extensive system that remains active long enough to enable the formation of a large deposit. Another factor to consider is the structural complexity associated with the tectonic environment; examples of this are the complex subduction zones of the western Pacific, characterized by subduction zone collisions, subduction reversals, rotations and microplate formation. In our research, we focused on the Mariana subduction zone to explore the occurrence of lithospheric-scale structures, using a combination of geophysical datasets including ship-based multibeam bathymetry, the Global Multi-Resolution Topography (GMRT) v3.9, seismic profiles, the global centroid-moment-tensor (CMT) catalog, the global 2-arc min Earth Magnetic Anomaly Grid and Vertical Gravity Gradient data. Preliminary results show a series of large-scale geophysical anomalies that cross the area longitudinally from the Mariana forearc to the Parece Vela Basin. We aim to investigate the nature of these anomalies and their possible controls on magmatism, permeability and large SMS formation.

REE mineralization style in carbonatites determined by wallrock interaction

Michael Anenburg
Research School of Earth Sciences, Australian National University, Canberra ACT, Australia

Carbonatites are the world’s principal source of the light rare earth elements (LREE: La, Ce, Pr and Nd). The REE are often hosted in monazite and REE-fluorcarbonates such as bastnäsite. These ore minerals are associated with a variety of carbonate minerals, but the exact mineral assemblage varies between carbonatites. Some REE mineralization occurs at the ferrocarbonatite cores of large alkaline–carbonatite igneous complexes, some occur within calcite-dominated dikes, while others may outcrop as weathered ironstone dikes and veins.

Carbonatite melts evolve and fractionate in predictable paths, in which calcite is the first carbonate mineral to crystallize, enriching the residual melt in Mg leading to later crystallization of dolomite. Further fractionation of both Ca and Mg leads to final enrichment of Fe, alkalis and the REE in a residual “brine-melt”. Crystallization of this brine-melt will result in an assemblage of ankerite and sodic REE carbonates such as burbankite. Burbankite often experiences late hydrothermal alteration removing alkalis and leaving behind monazite or bastnäsite pseudomorphs. However, late magmatic enrichment of alkalis and Fe is only feasible in the presence of surrounding silica-undersaturated rocks. In the case of surrounding silica-saturated rocks, the brine-melt is extremely unstable and will react with the wallrocks to consume Na, K, Mg and Fe, forming ferromagnesian silicates such as biotite, clinopyroxene and amphiboles. As these elements were the fluxes required to keep the carbonatitic brine-melt liquid, their removal freezes the melt to form a calcite-dominated rock in which monazite and bastnäsite crystallize directly without an intermediate burbankite phase. The dependence of the mineralization style and associated carbonate and silicate minerals on the silica contents of the surrounding rocks allows prediction of whether a carbonatite might be mineralized or barren, based on its gangue mineralogy and wider geological context.
Machine learning for automated detection of geophysical features associated with carbonatites and alkaline ring complexes

Malcolm Aranha
Indian Institute of Technology Bombay, Mumbai

Alok Porwal
Indian Institute of Technology Bombay, Mumbai; Centre for Exploration Targeting, University of Western Australia

Carbonatites and associated alkaline rocks are typically enriched in critical metals such as rare earth elements, U, Th, Nb, and in some cases, Cu, Au, PGE and diamonds. These rare rocks typically occur as ring complexes in extensional settings such as continental rifts associated with deep crustal faults with oval-to-circular ring-like or linear geometries. These features often show well-defined anomaly patterns in geophysical datasets, which can be used to map poorly exposed carbonatite-alkaline complexes in deeply weathered terranes and areas under thick sedimentary cover. The shapes and patterns of geophysical anomalies are generally visually analyzed and interpreted, which is time-consuming and often subjective. In this study, we develop a machine-learning workflow incorporating convolutional neural networks (CNN) with autoencoders for automated detection and extraction of geophysical anomaly features at a wide range of scales using progressively larger convolution filters. The anomaly patterns that persist at multiple depth levels are extracted and examined in the geological context to filter out artefacts. The workflow is demonstrated for mapping structural features associated with carbonatite-alkaline complexes in a study area in the state of Rajasthan, northwest India. The workflow leads to the delineation of major structural and morphological features that conform with the visually mapped and interpreted features in the study area. Our workflow can be applied to discover carbonatite-alkaline ring complexes from geophysical data in deeply weathered and under-cover terrains, and hence help in prospectivity assessments for critical-metal deposits associated with carbonatite-alkaline complexes.

Translating lithogeochemistry into petrophysics: vectoring to IOCG mineralization undercover

James R. Austin, Tobias U. Schlegel, Renee Birchall, Ben Patterson, Andreas Bjork, John Walshe, Helen McFarlane, Jessica Stromberg, Mark Pearce
CSIRO Mineral Resources

The classic status quo in geophysical exploration for IOCG (iron oxide-copper-gold) deposits is the “coincident gravity-magnetic high”. Whilst historically successful for IOCG exploration, it is not valid for many Cloncurry type deposits. An understanding of the lithogeochemical processes involved in IOCG formation, and their translation into petrophysical vectors, allows for a data-driven assessment of the physical zonation observed in and around IOCGs. Furthermore, these geophysical properties of metasomatically controlled geochemical zonation provide optimal exploration vectors in areas under cover. An integrated study on the Ernest Henry IOCG deposit identified a progression from early magnetite-dominant alteration to later, increasingly pyrite ± hematite-rich assemblages. Such zonation is typically explained by interaction of an oxidized fluid with a reduced host rock sequence but when viewed within a lithogeochemical framework it is also consistent with the neutralization of a relatively acidic fluid via fluid-rock interaction. A simplified model for the geophysical development of the Ernest Henry deposit results in a system with a moderately dense, highly magnetic medial footprint, outboard of a weakly magnetised, lower density proximal footprint, haloing a highly dense, moderately magnetic ore zone. Late hematite-quartz-chlorite-muscovite alteration in the ore zone resulted in replacement of magnetite by hematite causing subtle suppression of the magnetic signature. Consequently, coincident magnetic-gravity highs are not as favorable for IOCG exploration as might be expected, but targets with characteristic geophysical zonation, e.g. concentric magnetic zonation enclosing a second order gravity high, geophysically express more evolved (i.e. oxidized) IOCG systems, potentially waiting to be discovered. Although hematite is associated with the latest alteration stages at Ernest Henry, it is in low abundance relative to many deposits in the Gawler Craton, and recognition of more evolved IOCG’s undercover in the Cloncurry district may therefore require high resolution gravity data.
Comparative study of the greenstone and granitoid hosting orogenic gold in the Bétaré Oya and Colomine districts, eastern Cameroon: an overview

Kevin I. Azeuda Ndonfack, Yuling Xie
School of Civil and Environmental Engineering, University of Science and Technology Beijing, China

Richard J. Goldfarb
State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Beijing

Richen Zhong
School of Civil and Environmental Engineering, University of Science and Technology Beijing, China

Eastern Cameroon hosts several gold districts. The Bétaré Oya and Colomine districts are underlain by greenstones and granitoid, respectively. Gold-bearing quartz veins occur cutting both lithologies, particularly along the Bétaré Oya Shear Zone and the Colomine Shear Zone. Deposits share similar features including structures, ore mineralogy, fluid inclusions and O-H-C-S stable isotopes. However, metal trace elements (Bi, Cd, Co, Cu, Ni, Sb, V, W and Zn) concentrations are enriched in greenstone and depleted in gneiss and granitoid. Two mineral assemblages are distinguished with the first consisting of sulfides, Au-Ag-Te-Bi-bearing minerals and gold, and the second consisting of sulfides, tellurobismuthite, hematite and gold. Fluid inclusions provide evidence of episodic phase separation, with immiscibility at ~2 kbar, ~300–310 °C and paleodepth of ~6–9 km. The ore-forming fluid is of low salinity (~6.0-7.0 wt% NaCl equiv.) H₂O-NaCl-CO₂±N₂±CH₄ and daughter mineral phases including nahcolite, magnesite and arsenolamprite. The δ¹⁸Oquartz (+10.9 to +16.0 ‰), δDfluid (−50.6 to −21.8 ‰), and δ¹³Cfluid (−5.8 to −4.1 ‰) suggest a metamorphic source for the ore-forming fluids, but some contribution from mantle carbon cannot be ruled out. The δ³⁴S (+5.3 to +8.2 ‰) suggests a crustal source for the sulfur. The metamorphic source of fluids, structurual control of ore deposits, the enrichment of metal trace elements in greenstone and their depletion in gneiss-granite suggest that fluids and metals may have been expelled from host rocks in the earlier stage of metamorphism, specifically, during the transition from greenschist to amphibolite facies and then were deposited at the later stage of the Pan African Orogeny in eastern Cameroon.
Discrimination of magmatic-hydrothermal events using quartz texture and mineral chemistry

Michael J. Baker, Jennifer Thompson, Lejun Zhang
Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Tasmania, Australia

Quartz chemistry and cathodoluminescence (CL) textures can be used to help unravel the often complex paragenetic histories of magmatic-hydrothermal systems. Petrogenic studies have long shown that the morphology and crystallinity of quartz and other SiO$_2$ morphological varieties are dependent on their formation conditions; and now advancements in micro-analytical techniques (e.g. laser ablation ICP-MS) over the past 10-20 years have enabled researchers to collect low-level trace element data and understand the subtle geochemical variability that can be recorded in quartz grains over the lifespan of these hydrothermal systems.

Cathodoluminescence imaging and LA-ICP-MS analysis of hydrothermal quartz from the behemoth El Teniente porphyry Cu-Mo deposit in central Chile have revealed several stages of paragenetic growth, coupled with measurable changes in quartz pathfinder element concentrations. Hydrothermal quartz textures include CL-bright colloform zones and CL-bright to CL-dark concentrically zoned grains. These quartz textures are found exclusively within hydrothermal veins up to 2 km from the mapped extent of economic copper mineralization. The hydrothermal quartz grains also show spatial variability in trace and pathfinder metal concentrations. Notably, Ti in quartz concentrations decrease from the edge to core of hydrothermal veins and can also be used to indicate a change in temperature of formation from early high-T to late lower-T using published quartz geothermometer calculations.

The spatial variability in pathfinder metal concentrations (e.g. Sb, Li) in quartz may be linked to lateral metal dispersion from the loci of hydrothermal activity at El Teniente. In the analyzed samples, Ti and Cu concentrations in quartz show a general increase, and Fe, Sb, Li, Al and As show a general decrease towards the deposit centre. These characteristics make it possible to use trace element ratios (e.g. Ti/Sb) to model hypothetical distances from mineralization, which makes quartz mineral chemistry a useful tool for base metal exploration.
The Potassium Mobility Index (KMI): an XRF-appropriate discriminator for sericitic and chloritic alteration

Tobias Bamforth
*Murdoch University, Perth, Western Australia, Australia*

Siyu Hu, Ignacio González-Álvarez
*CSIRO, Kensington, Western Australia, Australia*

X-ray fluorescence (XRF) analyses, such as those measured by Minalyzer Core Scanner (CS) systems and portable-XRF devices, offer a cheap, rapid and non-destructive method of geochemical data acquisition; however, the inability of XRF technologies to measure certain element concentrations (i.e. Na) limits their practical application when such measurements are required for the determination of traditional geochemical vectors. For instance, the Alteration Index (AI) and the Carbonate-Chlorite-Pyrite Index (CCPI) are often used to separate zones of chloritization and sericitization across volcanogenic massive sulfide (VMS) deposits – though neither are determinable by these XRF analyses alone.

This study applies K-means clustering and Principal Component Analysis (PCA) to Minalyzer CS drill core data from the Woodlawn VMS deposit, New South Wales, to: (1) chemically differentiate between discrete zones of mineralization and alteration in a mathematically-robust manner, and; (2) develop an XRF-appropriate vector for VMS-style alteration. The clusters derived by K-means analysis demonstrate excellent separation between zones of mineralization, chloritization and sericitization that conform with the alteration mineralogy. Subsequent plotting of these clusters by PCA highlights their unique elemental associations, from which the novel Potassium Mobility Index (KMI) is derived as a discriminator for sericite-chlorite alteration: KMI = (V/K)*100.

Statistical analysis of KMI values generated from the Woodlawn samples demonstrate how values of KMI > 2 denote zones of ore-proximal chloritic alteration, while values of KMI < 0.03 indicate zones of distal sericitization. Further, these values generate a gradational continuum (whereby KMI = 0.03 – 2 is transitional), which can be applied as a quantitative vector to mineralization. Overall, this work demonstrates how: (1) the KMI may be used as an XRF-appropriate discriminator and vector across both the Woodlawn deposit and other VMS-type alteration envelopes; and (2) statistical studies on compositional datasets may be conducted to further ore modeling and exploration approaches.
Genesis of gold mineralization in the Pahardiha–Rungikocha gold deposit, North Singhbhum Mobile Belt, eastern India: a geochemical and mineral-chemical approach

Anmol Barla, Sahendra Singh
Indian Institute of Technology (Indian School of Mines), Dhanbad, India

Rajarshi Chakravarti
Indian Institute of Technology, Roorkee, India

The Pahardiha–Rungikocha gold deposit is situated along the western margin of the gold-endowed Proterozoic North Singhbhum mobile belt in eastern India. The total gold ore resource reported from the deposit is 0.487 Mt with an average grade of 3.43 ppm. The deposit is characterized by the presence of low-grade metasedimentary rocks with gold mineralization confined to sheared quartz-chlorite schists. In this deposit, gold occurs as native specks hosted within fractures and along the grain boundaries of euhedral pyrite. Field observations combined with petrographic evidence suggest the mineralization to be post peak-metamorphic (along displacement fractures), possibly representing the D3 deformation event. A unique feature associated with the deposit is the ubiquitous presence of chromite-cored magnetite. Paragenetic studies coupled with EPMA and LA-ICP-MS trace element signatures of the chromite-cored magnetite suggest that relict chromite was altered during progressive metamorphism (D1-D2). This was followed subsequent shearing and associated metasomatism (D3) leading to the epitaxial growth of magnetite on pre-existing chromite, and simultaneous precipitation of gold. The host quartz-chlorite schist had an intermediate to mafic protolith as evident from bulk-rock geochemistry, presence of relict chromite and elevated Ni, V contents. Interestingly, trace element trends of the chromite-cored magnetite are strikingly similar to the bulk-rock trace element trends, thereby suggesting that bulk-rock chemistry had a first order control on magnetite chemistry. Unlike pyrite grains of hydrothermal origin, euhedral Au-bearing pyrite here exhibits relatively high Ni values compared to that of Co, as seen from pyrite LA-ICP-MS trace element data. Given the absence of a causative intrusion and the inferred control of bulk-rock chemistry on the composition of magnetite and auriferous-pyrite, we conclude that gold here was derived in-situ, i.e. derived from a pre-enriched wall-rock and concentrated to ore-grade during the D3 deformation event (bulk-rock Au ranges from 0.6 - 1844 ppb, n=16).
Nickel depletion and enrichment in olivine in mafic-hosted Ni-Cu sulfide systems

Stephen J. Barnes
CSIRO, Mineral Resources, Kensington, Perth, Australia

Zhuo-Sen Yao
Department of Earth Sciences, Carleton University, Ottawa, Canada

Ya-Jing Mao
Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, CAS, Beijing, China

Ana P. Jesus
Instituto Dom Luiz, Lisbon, Portugal

Nickel contents of olivine have been widely used as petrogenetic indicators and as fertility indicators for magmatic sulfide potential of mafic-ultramafic intrusions. We identify multiple sources of variance in Ni content of olivine at given Fo content, including: variability in mantle melt composition due to melting depth, water content and possibly source; subsequent fractional crystallization with and without sulfide; recharge and magma mixing; batch equilibration between olivine and sulfide at variable R and olivine/liquid ratio; and subsequent equilibration during trapped liquid crystallization in orthocumulates. Baselines for Ni in olivine in relation to Fo content are somewhat lower in orogenic belt settings relative to intrusions in continental LIPs but both groups contain olivine with higher Ni contents than expected for modeled crystallization products of normal mantle melts. No clear, universal discrimination is evident in Ni in olivine between ore-bearing and barren intrusions even when tectonic setting is taken into account. However, sulfide-related signals can be picked up at intrusion scale in many cases. Low-R factor, low-tenor sulfides are associated with low-Ni olivines in several examples and these cases stand out clearly. Anomalously high-Ni olivines are a feature of some mineralized intrusions, in part due to trapped liquid reaction effects. However, in some cases, this mechanism cannot account for the magnitude of enrichment and enrichment may be due to re-entrainment of "primitive" Ni-rich sulfide by a more evolved Fe-rich magma, driving the olivine to become Ni-enriched due to Fe-Ni exchange reaction between sulfide and olivine. An extreme case of this process may account for ultra-Ni enriched olivine at Kevitsa (Finland), but more subtle signals elsewhere could be positive indicators. Wide variability of high and low Ni at similar Fo may be as useful a fertility indicator as are simple depletion signals, reflecting equilibration in periodically recharged magmatic conduits.
Beyond conventional geometallurgy: a broader view to be prepared for a circular economy

Regina Baumgartner
Teck Metals Ltd, Trail, British Columbia, Canada

Orebody knowledge is foundational to geometallurgy in which the focus has changed from the well-known traditional geometallurgy to one integrating a broader view towards the global transition into low-carbon technologies and economy, with the potential to unlock future unknown resources. Optimization of the known, for example, a copper resource from a porphyry copper deposit, is now extended to the optimization of not only the copper product but other valuable elements present in ore and non-ore materials and/or potential products sourced from non-ore materials and tailings (e.g. construction materials and concentrates via reprocessing). These optimization and de-risking processes are related to the mining value chain which now would be viewed as a value circle or wheel rather than a chain since we now have the potential to produce new products from residual materials.

Complex orebodies in which ore and non-ore materials are considered need enhanced orebody knowledge to unlock future resources by identifying, assessing and testing the economic value using advanced analytical techniques including applied mineralogy, chemical analytical methods, novel core scanning and microanalytical tools complemented by novel mineral processing techniques. Optimising the application of microanalytical tools is of particular significance because the occurrence of various economic elements in different minerals requires analysis and characterization at variable scales from millimeters to microns. Therefore, routine chemical assay procedures will not provide information on the occurrence or deportment of additional valuable elements. Furthermore, analytical packages routinely used in assay campaigns do not include some critical elements (e.g. REE) or have inappropriate lower detection limits.

Data collection through orebody knowledge initiatives need to be combined with other data and tests via data integration to make geometallurgy successful. Integration can be accomplished by advanced tools such as machine learning and to do this, a team validation is needed to ensure that geological, processing, mining and/or environmental aspects, are appropriate and will be embedded in current and future geometallurgical models or reclamation activities.

Hydrothermal versus protolith compositional controls on the metal endowment of VMS deposits in proto-arc terranes

Thomas M. Belgrano, James A. Milton, Damon A.H. Teagle
School of Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton

Larryn W. Diamond
Institute of Geological Sciences, University of Bern

The lavas of the Samail ophiolite, Oman host numerous volcanogenic massive sulfide (VMS) deposits. The Au/Cu ratios of these deposits increased progressively both with time and subduction-zone influence. The exceptionally complete exposures of the Samail VMS mineral systems allows us to test rival hypotheses for the controls on these progressions via precise measurements of elements such as Cu, Au, Zn, Ag, As, Pt and Re in suites of volcanic glasses and rocks, and in the ores themselves. Measurements of these ultra-trace chalcophile elements in both volcanic whole-rocks and glasses were performed by a novel LA–ICP–MS technique suited to rapid analysis of large suites of samples. Using this data, we establish a correlation between the Au/Cu ratios of each generation of VMS deposits and their footwall volcanic unit. Paleobathymetric studies rule out seafloor shallowing and attendant boiling-enhanced Au precipitation at vent sites, supporting a footwall rock compositional control on the Au–Cu endowment of VMS deposits formed in proto-arc, subduction initiation settings.
Geology and genesis of the giant Gorevskoe Pb-Zn-Ag deposit, Krasnoyarsk Territory, Russia

Georgii Belokonov1,2, Max Frenzel1, Nadezhda Priyatkina3, Axel D. Renno1, Vladimir Makarov2, Jens Gutzmer1
1 Helmholtz-Zentrum Dresden-Rossendorf, Institute Freiberg for Resource Technology, Germany
2 Siberian Federal University, School of Mining, Geology and Geotechnology, Russia
3 Institute of the Earth Sciences, St. Petersburg State University, Russia

The Gorevskoe Pb-Zn-Ag mine exploits one of the largest sediment-hosted Pb-Zn deposits worldwide. Despite its size and economic importance, the Gorevskoe deposit remains poorly understood. It is located on the western margin of the Siberian Craton within the Yenisei Ridge, a Neoproterozoic orogenic belt. Mineralization consists of three tabular orebodies that are in turn composed of multiple stacked stratiform to stratabound lenses of galena-pyrrhotite-sphalerite-rich massive sulfide ore, hosted in organic-rich marine metalimestones and calcareous slates of Stenian to Tonian age (1,020 ± 70 Ma). Extensive Fe-Mg-Mn-carbonate alteration haloes surround the ore lenses. The Pb isotope signature of the deposit is consistent with derivation of Pb, and probably all associated metals, from an evolved crustal source at the time of formation of the host rocks. The sulfur-isotopic compositions of pyrrhotite, sphalerite, galena, arsenopyrite and pyrite (δ34S = 16.0 – 20.4 ‰) do not vary considerably across the deposit and are within the range reported for contemporaneous seawater, indicating complete reduction of marine sulfate as the main source of sulfur.

The available geological and geochemical data indicate that the Gorevskoe deposit belongs to the sediment-hosted massive sulfide (SHMS) class of Zn-Pb deposits, with an affinity to Selwyn-type deposits. Hydrothermal mineralization appears to be temporally related to rifting and distal mafic volcanism in a passive margin setting. Geological relationships suggest that the orebodies formed in a diagenetic environment. Furthermore, the predominance of primary pyrrhotite over pyrite as the major iron sulfide, the presence of abundant siderite, and the relatively homogeneous sulfur isotope signature of the ores indicate highly reducing conditions during ore-formation. They also constrain the character of the metal-bearing fluid to be similarly reducing, and of moderate temperature (200 – 300°C). Gorevskoe may thus be regarded as one of the world’s largest Selwyn-type SHMS deposits.
Feldspar and muscovite chemistry from Be-Nb-Ta mineralized Yamrang Pegmatite, Eastern Nepal

Sushmita Bhandari1,2,3, Kezhang Qin1,2
1Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, CAS, Beijing, China
2University of Chinese Academy of Sciences, Beijing, China
3Department of Mines and Geology, Kathmandu, Nepal

Although the Nepal Himalaya is famous for aquamarine, its detailed occurrence, mineralization characteristics and host-rock properties are poorly constrained. Our research represents the first detailed study of aquamarine-bearing pegmatites from Nepal Himalaya where we discovered the zoned, Be-Nb-Ta Yamrang Pegmatite. We differentiated the pegmatite into five zones in which Be-Nb-Ta mineralization is concentrated within zones 3, 4 and 5. Samples of feldspar and muscovite from the five zones were analyzed for major and trace elements by EPMA and LA-ICP-MS. Feldspar contains Nb-Ta below detection level (bdl), Rb (bdl-2925 ppm), Cs (bdl-323 ppm), Ba (bdl-462 ppm), Ga (bdl-30 ppm) and P (22-906 ppm). K/Rb values ranges from 46 to 1838, K/Cs is 375-13259, and Rb/Sr is up to 2259. Muscovite contains Li (256-696 ppm), Be (18-47 ppm), Rb (774-6881 ppm), Cs (14-621 ppm), Ba (1-50 ppm), Nb (69-701 ppm), Ta (5-176 ppm) and Ga (87-181ppm). K/Rb value ranges from 18 to 140, K/Cs is 199-7900, Rb/Sr is 170-19660 and Nb/Ta is 2-17. The median values of K/Cs, Ba and Ti of feldspar, and K/Rb and K/Cs of muscovite increase from zone 1 to 2, and then decreases systematically from zone 2 to 5. In contrast, the Ga and P contents of feldspar increase from outer zones to inner zones. K/Cs and K/Rb ratios were lowest in zone 5 and highest in zone 2. Feldspar with K/Rb 30-150 ppm, Rb ~3000 ppm, Cs >100 ppm, and muscovite with K/Rb 18-50, Rb ~6000 ppm, Cs >500 ppm and Ta >65 ppm were found in inner zones (3-5), indicating that the Yamrang pegmatite is an intermediate-fractionated, beryl-type REL pegmatite, with fractionation trend from outer to inner zones. Higher P and Ga, and lower Ba and Ti contents in feldspar are potential evolution indicators in the region. This study demonstrates the value of trace element analysis and further suggests the potential for as-yet-undiscovered rare-metal mineralization in the region.
Linking complex vein paragenesis with kyanite growth and copper sulfide mineralization at low temperatures in the Congolese Copperbelt

Anna K. Bidgood, Murray Hitzman, Helen Twigg, Sean Johnson
Irish Centre for Research in Applied Geology, University College Dublin

David Chew
Trinity College Dublin

Kyanite (Al₂SiO₅) is traditionally considered a high-pressure, high-temperature mineral. Common kyanite-forming reactions such as pyrophyllite or chlorite dehydration take place at ~ 400°C and >600°C respectively. The occurrence of kyanite in the low pressure-temperature rocks at the Menda prospect in the southern Democratic Republic of Congo indicates unusual conditions of kyanite growth. The Central African Copperbelt (CACB), the world’s primary source of copper, produces about 70% of the cobalt which is critical for battery production needed to decarbonize our societies. Here, kyanite is observed within low temperature magnesitic carbonates hosted in a post-evaporitic breccia, associated with abundant chalcopyrite. Kyanite occurs in multiple different textural generations including as host rock porphyroblasts, vein- and fracture-hosted.

Detailed petrography combined with cathodoluminescence imaging and element mapping by laser ablation mass spectrometry are used to unravel the vein paragenesis which is much more complex than immediately apparent in core/hand specimen. Kyanite preserves evidence of fluid-mediated alteration which is supported by trace element compositions. Carbonates within the primary magnesite veins reveal a complex growth history, followed by later replacement and alteration by magnesite and dolomite.

Highly saline fluids are associated with extensive mineralization and alteration in the CACB. The intimate association of kyanite-magnesite-monazite-quartz veins that contain chalcopyrite strongly suggest that unusual and changing fluid and thermodynamic conditions played a role in the genesis of the Copperbelt Cu-Co system. The occurrence of kyanite in carbonates and veins suggests that immobile metals, such as Al, have been transported in these unique fluid conditions. Understanding the paragenesis of kyanite in relation to Cu, Ni and U mineralization, as well as the unusual thermodynamic conditions required for low-temperature kyanite growth and Al-mobilization, has implications for the interpretation of the metamorphism in the Domes region of the Zambian Copperbelt, and for understanding the unique fluid fingerprints for future exploration models.

Hybridization of mines in Africa through a reform of legal regimes and statutes on renewable energies

Mike Vianney Bidjo Mbonomo
National Advanced School of Mine and Petroleum Industries, University of Maroua, Kaele, Cameroon

The desire for many countries in sub-Saharan Africa (e.g. Cameroon, Mali and Congo) to transition from mostly artisanal mining to modern mining is limited by restricted energy supply. Studies by the World Bank have demonstrated the gap between their mining potential and the availability of energy required to meet this potential. New energy generation and better utilization of energy is required in order to reduce the dependence on fossil fuel energy in the mining industry and with a view to developing the strong potential of these countries for clean energies. To this end, the hybridization of mines in Africa aligns with the objectives of reducing pollution for a carbon-neutral environment. It involves decarbonizing mining operations by using hybrid systems such as a combination of solar, wind, virtual synchronous machines, storage and load control. However, new energy generation is hampered by inadequate, policies regarding renewable energies for stimulating this sector. Development of the renewable energy sector requires the existence of an appropriate policy and regulatory framework facilitating the deployment of state institutions, private operators and taking initiatives at all links in this development chain. Encouragement of academic research and establishment of appropriate training institutions are also required.
Hydrothermal wall rock alteration related to Late Variscan Pb-Zn-Ag-(Au) mineralization and its implication for exploration in the Freiberg District, Germany

Sandra Birtel, Jens Gutzmer
Helmholtz Zentrum Dresden Rossendorf, Helmholtz Institute Freiberg for Resource Technology, Germany

Although epithermal Pb-Zn-Ag-(Au) vein-hosted mineralization in the Freiberg District, Germany, has been widely studied, closely associated wall rock alteration remains poorly understood. In order to deduce alteration stages in the proximity to mineralized veins, suites of wall rock samples ranging from least altered to intensely altered were studied from two localities in the central part of the district in order to describe and quantify the effects of hydrothermal wall rock alteration.

Least altered host rocks at both localities are medium- to coarse-grained biotite-plagioclase-orthoclase augen gneisses. In weakly altered samples the foliation, and the primary assemblage, are well preserved with typical alteration assemblages comprising fine-grained carbonate, kaolinite, epidote, sericite and chlorite. This alteration assemblage also dominates the moderately altered samples, with metamorphic quartz and the original foliation partly preserved. In contrast, the intensively altered samples comprise a massive fabric with globular quartz and fine-grained sericite that are very finely intergrown. Arsenopyrite and/or pyrite occur finely disseminated in this alteration assemblage. Fe-Mn-rich carbonates also occur in the matrix or as thin veinlets in the altered wall rock. In hand specimen, this strongly sericitized rock is of light green to yellow color.

Hydrothermal alteration related to vein-hosted, magmatic-hydrothermal mineralization in the Freiberg District destroys the original metamorphic fabric, an effect that can be simply detected visually in core. Sericitization and silicification are dominant and appear limited to the immediate vicinity around and within relevant structural zones and veins. Visual core inspection, possibly complemented by hyperspectral drill core scanning and lithogeochemistry (by pXRF), are simple tools that can be used to trace this alteration during ongoing exploration efforts in the district.
The origin of Cu-(Te-Au-Ni-PGE) sulfide deposits of the Curaçá Valley, Brazil: can tellurium settle the genetic debate?

Daryl Blanks, David A. Holwell
University of Leicester, United Kingdom

John Thompson
PetraScience Consultant Inc, Canada

Ingrid Mota, Filipe Porto
Ero Copper, Canada

The Curaçá Valley hosts a suite of mineralized phlogopite-rich ultramafic/mafic intrusions residing within the Itabuna-Salvador-Curaçá Orogenic Belt, Brazil. The origin of the Cu-sulfide mineralization is highly debated, with three main models proposed; Cu-rich fractionated magmatic sulfide, hydrothermal/metamorphosed magmatic sulfide, and an iron oxide copper-gold (IOCG) origin.

Massive sulfide at the Vermelhos and Pilar mines are dominated by chalcopyrite and bornite associated with Cr-rich magnetite, with minor Fe-sulfides. Disseminated mineralization in ultramafic/mafic rocks is predominantly bornite and chalcocite in lieu of chalcopyrite. Pentlandite and millerite are sporadic but typically associated with massive sulfide and coincide with higher grades of platinum group elements (PGE). Furthermore, the ores display an extremely high Te content, up to 450 ppm, with abundant tellurides (mostly melonite; NiTe2) present within the Cu-rich sulfide assemblage.

A consistent feature of the ores is an association with phlogopite, which shows a number of textural associations that often appear to be primary and co-genetic with the sulfides. Carbonate, as calcite, is rare but when present occurs as rims around sulfide patches in phlogopite-rich samples.

Whilst it is possible that mineralization is associated with a fractioned Ni/Cu-magmatic system, and/or has been subject to intense hydrothermal and metamorphic activity, the volatile and highly Te-enriched mineralization of the Curaçá Valley deposits is also consistent with the recently recognized metallogenic signature found in lower and mid crustal ultramafic/mafic alkaline systems. In these systems, sulfides exhibit high Cu/Ni ratios, are associated with carbonate, phlogopite, apatite and other volatile-bearing phases, and are enriched in Te and Au, with minor Pt and Pd.

We utilize a global database of base metal and Te data from a range of magmatic and IOCG deposits to test these genetic models for mineralization at Curaçá, and show that the Te content in particular, is an excellent tracer of mantle source composition, degree of partial melting, and sulfide fractionation.
Indium mineralization from Zlatý Kopec skarn deposit: complex metallogeny of Fe–Sn–polymetallic skarn-hosted mineralization in Krušné hory/Erzgebirge Mts

Petr Bohdalek, Ondřej Pour, Irina Andronikova
Czech Geological Survey

The Zlatý Kopec skarn deposit of western Krušné hory Mts (Erzgebirge) is hosted by various phyllitic rocks (graphite bearing, garnet-bearing and albite-bearing) of probably early Paleozoic age with inlayers of quartzitic rocks and metabasites indicating primarily volcanosedimentary character of pre-metamorphic sedimentary protoliths. Skarns form irregular lenticular stratiform bodies, but signs of skarnization-like processes can be observed also in phyllite host rocks. Skarn bodies are mineralized in at least four stages, all probably connected with an underlying granite intrusion although some first skarnization stages can be caused by fluids originated during the peak of metamorphism at 340 Ma. Nevertheless, there are three mineral assemblages representing typical magnesian tin-bearing skarns with early an anhydrous diopsidic-pyroxene – magnetite – cassiterite assemblage, followed by a magnetite – borate assemblage (magnetite + szaibeleyite + hulsite + fluoborite) and later a retrograde hydrous skarn assemblage represented by amphibole, chlorite and serpentine. These three mineralization stages are connected with metasomatic fluids released from underlying tin-bearing granites with locally developed endo-greisen mineralization. The sulfide-bearing mineralization stage can be caused by either the latest stage of greisen-like fluids, or hydrothermal fluids of successively cooling magmatic - hydrothermal system, or both. Indium mineralization occurs as In-bearing sphalerite associated with chalcopyrite. Up to 12% In occurs in Fe-rich sphalerite, whereas chalcopyrite contains only up to 0.2% In.

The original characteristics of the volcanosedimentary protoliths are very interesting. Some telluride and selenide minerals, together with Ni and Fe arsenides occur in the skarn and surrounding skarnized phyllites, indicating a weakly mineralized volcano-sedimentary environment of possible island-arc type. The locality represents a typical example of a magmatic – hydrothermal system an ancient collisional orogen.
Global lithium production has experienced a boom since the 2010s. The increase in demand is fueled by its use for energy storage. Lithium-Ion Batteries are used in the information, communication and technology sector, as well as in the automotive sector where electric vehicles (EVs) are expected to provoke a major revolution. This global context of energy transition has led to a ‘white gold rush’, a global fever of lithium exploitation of both hard-rocks and brine deposits. This global race towards the deposits, especially in Latin America’s ‘Lithium Triangle’ and Australia, is deeply reconfiguring its Global Production Networks.

This paper explores the specific trajectories of lithium exploitation in Australia and Latin America through an in-depth analysis of the materialities of its lithium industries. Together, these regions are the largest producers of lithium, with over 75% of global production. The lithium industries in these regions hold certain similarities: mining territories are located at national peripheries where Indigenous communities live, the industry includes major and minor producers, and exports are directed at similar markets. However, a key difference remains: lithium is extracted mainly from ores in Australia and from brines in Latin America, with differing times and modes of production. The materialities of lithium are here explored through the spatial embeddedness of the industry and the associated infrastructure developed to extract and circulate it over space. The length of infrastructures (e.g. roads, railways, deep water port and energy lines) allows us to read and understand the different lithium landscapes. This includes a focus on governance, including the local, regional, national and global levels of governance of the mining territories and their multiple stakeholders, as well as the socio-spatial forms of integration of mining sites through interdependent relationships between spaces (deposits), stakeholders (states, the mining industry, populations) and the environment (culture and society).
The mining company in New Caledonia: relying on the customary Kanak network to sustain nickel extraction?

Valentine Boudjema

Doctoral student in geography, ISEA, University of New-Caledonia, UMR 228 Espace DEV, IRD Nouméa

In New-Caledonia, the nickel industry induced numerous public policies, from addressing the issue of spatial rebalancing (e.g. Matignon-Oudinot agreements more than thirty years ago), to economic diversification, a paradigm of the “post-industrial era of nickel”. These policies are constantly reflected in discourse but are prevalent during recessions in the sector, which remind us of the need to endorse development of the territory by considering the mine as a constraint as much as a resource. The “Mines and Territories” project funded by the CNRT-Nickel Consortium questions the impacts of the mine on the development of the territory.

Doctoral research, based on one hundred and twenty semi-structured interviews and fourteen weeks of observation in the field, aims to better understand how a mining territory and its margins are built, by focusing in particular on material and immaterial movements between the two spaces.

The presentation will be based on the following hypothesis: to ensure the continuity of a mining project and the sustainability of a pacifist agreement with local communities, the mining operator carves a place for itself within the customary networks of Kanak tribes. First, the Kanak social organization will be described. Then, this tribal anchoring is allowed by a specific actor, the person in charge of corporate social responsibility (CSR) who works on both aspects: the cooperation between the actors of the sector and the structuring of the local populations. Such an actor innovates socially by proposing new models of governance or by re-appropriating tribal associations. Two examples will illustrate this point, the company SAS Vavouto and the tribal associations.
3D geological–geophysical–geochemical modeling of the Russell Lake property (Saskatchewan, Canada): targeting/discovering basement-hosted uranium deposits

Joseph A. Bravo¹, Irvine R. Annesley¹,², Zoltan Hajnal², Tobias Bauer³
¹ENSG, Université de Lorraine
²University of Saskatchewan
³Luleå University of Technology

The Paleoproterozoic to Mesoproterozoic Athabasca Basin, northern Saskatchewan, is well known for hosting the world’s highest-grade uranium deposits. However, as most of the near-surface deposits have been already discovered/exploited, deeper basement-hosted U deposits are being targeted; increasing the need to develop new strategies, e.g. 3D/4D geomodeling, to optimize exploration at depth. Our research adds knowledge to basement-hosted U exploration by constructing a comprehensive 3D geological model of the Russell Lake property, Saskatchewan. Using Emerson SKUA-GOCAD and Geoscience ANALYST Pro, a geomodel was developed in two stages. First, a regional to district-scale model (eastern Athabasca) was built based on free 3D objects from the Saskatchewan Geological Survey. Then, geological/geophysical maps and a regional seismic reflection (Line S2B) added detail to the model. Secondly, a district to property-scale model was built based on the interpretation of migrated high-resolution seismic profiles of two seismic reflection surveys (2004, 2005) on the Russell Lake Property. The modeling workflow incorporated visual inspection/interpretation of the seismic profiles, correlation with geological/geophysical maps, and structural lineament analysis of the area. Additional software packages (OpendTect, SeismiGraphix, Oasis Montaj, ArcGIS, QGIS) were used to facilitate data interpretation. The results reflect the structural complexity related to the Trans-Hudson Orogeny. The model suggests that large basement-sourced fault zones of different generations (trends and ages) interconnected (in part) through time and space served as pathways/precipitation sites for mineralizing fluids. The reactivations of these zones are associated with offsets in the unconformity and late sub-vertical brittle events. Moreover, some large fold-and-thrust structures appear listric to a prominent seismic reflector at depth, whereby younger brittle faults intersect and offset this reflector. The latter, in conjunction with basement age constraints, may imply its initial age. In summary, the 3D model allows the identification of favorable structural-geochemical zones that can host U mineralization (e.g. the M-Zone).
Permeability available for hydrothermal leaching of VMS metals from basaltic lavas: Semail ophiolite, Oman

Alannah C. Brett, Larryn W. Diamond
Institute of Geological Sciences, University of Bern, Switzerland

The distribution of permeability in the upper oceanic crust controls the extent to which hydrothermal solutions can leach metals and transport them to seafloor vents and VMS deposits. A prevailing view is that the lavas behave as a fractured aquifer in which permeability is dominated by extensional faults and fracture networks. This implies that the volume of lava accessible for metal leaching is limited to fracture walls. In fact, little is known about the nature of fracture networks and about the permeability of the rock matrix in the km-wide blocks of hydrothermally altered lavas that lie between major faults. To bridge this gap we characterized the distribution of permeability in fault-distal blocks pervasively altered to greenschist-facies spilite (chl+alb±act) in the MORB-type lavas of the Semail ophiolite. Upscaled measurements of rock-matrix porosity and permeability yielded outcrop-scale permeabilities of ~2.5 \( \times 10^{-16} \) m\(^2\), similar to that of fresh basalt. Mapping of hydrothermal veins as proxies of syn-alteration fractures revealed low fracture connectivity and low intensities of only ~0.005 m of fracture per m\(^2\) of outcrop, an order of magnitude lower than in fault-damage zones. Numerical simulations (using dfnWorks software) of coupled fracture-controlled and rock-matrix flow through ~500 m size lava blocks yielded a bulk permeability of ~5 \( \times 10^{-16} \) m\(^2\), only double that of the matrix alone. These results demonstrate that in fault-distal blocks the hydrothermally altered rock matrix is as permeable as the sparse and poorly connected fracture network. This is consistent with the thoroughly pervasive, rather than fracture-controlled, nature of greenschist-facies hydrothermal alteration observed in the Semail lavas. This updated view of fluid flow implies that the entire volume of lavas in the upper oceanic crust is accessible for leaching of VMS metals during hydrothermal circulation, with discharge enhanced by subvertical fault-damage zones at km-scale intervals.
Zircon as an exploration tool for iron-oxide copper-gold mineralization

Adrienne Brotodewo, Caroline Tiddy, David Giles
Future Industries Institute, UniSA STEM, University of South Australia, Mawson Lakes, South Australia, Australia
Mineral Exploration Cooperative Research Centre (MinEx CRC)

Diana Zivak
Department of Earth Sciences, University of Adelaide, Adelaide, South Australia, Australia

Adrian Fabris
Geological Survey of South Australia, Department of Energy and Mining, Adelaide, South Australia, Australia

Shaun Light, Ben Forster
OZ Minerals Limited, Adelaide, South Australia, Australia

Zircon preserves unique geochemical signatures that reflect crystallization environments and post-crystallization modification that can be directly linked to mineralizing events. Research relating to zircon has largely focussed on the development and application of zircon geochemical criterion in porphyry Cu-Au systems. However, minimal research has been undertaken when looking at how zircon chemistry varies within other mineralizing systems, such as iron-oxide copper-gold (IOCG) deposits.

Here, we demonstrate that zircon associated with IOCG deposits display a unique trace element chemistry compared to zircon within barren rocks, and that this geochemical signature can be used as a tool for understanding proximity to IOCG mineralization. The Carrapateena IOCG deposit in the Gawler Craton, South Australia, is used as a case study, where the chemistry of zircon hosted within mineralized (altered) and unmineralized ~1850 Ma Donington Suite granitoids is compared. The variation in zircon chemistry is used to propose geochemical criteria using zircon for IOCG deposits where zircon from within areas of mineralization displays elevated Eu/Eu* and HREE Fractionation (Gd/Yb) content.

This study also shows that the unique zircon geochemical signature associated with the IOCG mineralizing system at Carrapateena can be recognized in zircon hosted within the cover sequence materials directly overlying the deposit, implying that zircon can withstand processes of erosion, weathering, transportation and redeposition. The presence of zircon derived from the mineralized basement in the younger cover sequence shows that the zircon geochemical footprint of the mineralizing system has the potential to be dispersed, which aids exploration under cover.
Hydrothermal signatures in Lower Carboniferous carbonates in the Irish orefield: recent geological and geochemical advances in understanding ore genesis and providing exploration vectors

Erie Burton1,2, Aileen Doran1,2, Lingli Zhou1,2, Koen Torremans1,2, Julian Menuge1,2, Steven P. Hollis1,3, Lola Yesares1,4, John Guven1,2, Murray Hitzman1,2

1Irish Centre for Research in Applied Geosciences (iCRAG), Belfield, Dublin, Ireland
2School of Earth Sciences, University College Dublin, Belfield, Dublin, Ireland
3School of Geosciences, University of Edinburgh, Edinburgh, United Kingdom
4Mineralogy and Petrology Department, Complutense University of Madrid, Av. Complutense s/n, Madrid, Spain

Recent work has advanced our understanding of the structural, geochemical and isotopic systems in the Irish orefield. The Irish orefield contains Zn-Pb-(Fe) deposits hosted in Lower Carboniferous carbonate rocks which occur adjacent to normal faults. The Rathdowney Trend consists of a ramp-relay array of normal faults which parallel the Iapetus Suture and were active during Carboniferous sedimentation. The Navan deposit lies astride a major extensional horst block along the Iapetus Suture with individual orebodies in more permeable lithologies adjacent to subsidiary normal faults along the crest and steep flank of the block. Productive faults in both deposits were conduits during the Carboniferous for fluids which had interacted with basement rocks to mix with cooler fluids derived from seawater. Zones of fluid mixing resulted in replacement and dissolution of calcite and locally dolomite in the host carbonate lithologies, and essentially synchronous precipitation of dolomite, sulfide minerals, and lesser barite, quartz, calcite, iron oxide minerals and apatite. Recent trace element research indicates that Ge was incorporated into sphalerite in several deposits resulting from coupled substitutions, controlled by the specific compositions of the hydrothermal fluids. Studies have identified how traditionally untargeted critical metals, primarily Ge with minor Ga and In, might be recovered as smelting by-products or from historic tailings. Ongoing Pb isotope studies demonstrate that Pb isotopes in galena displays micro-scale zonation with the largest isotopic variations present in the largest orebodies, suggesting that such variations are related to different fluid flow paths within the pre-Carboniferous basement rocks beneath the deposits. Clumped C-O isotope analyses have provided new fluid temperature and fluid O isotope composition constraints. Current results suggest significant fluid temperature variations between ore and non-ore stage carbonates in multiple Zn-Pb deposits. The research results are providing new avenues to discern vectors for exploration in the orefield which may be applicable in other districts worldwide.
Unveiling the polyphasic evolution of the IOCG Salobo deposit, Carajás Mineral Province, Brazil: insights from magnetite trace elements and sulfur isotopes

Yuri T. Campo Rodríguez, Maria E. Schutesky Della Giustina, Claudinei G. de Oliveira
University of Brasília

Martin Whitehouse
Swedish Museum of Natural History

The Salobo iron oxide copper-gold (IOCG) deposit hosts important Cu mineralization in the Carajás Mineral Province (CMP). The ore is characterized by an association of bornite-chalcocite-digenite hosted by magnetite and biotite-garnet schists, which record superimposed hydrothermal alteration and dynamic metamorphism. Three magnetite occurrences are present: pristine to inclusion-poor Mgt I; inclusion-rich magnetite-bearing breccia Mgt II; and granoblastic-foliated Mgt III. The magnetite presents a similar trace element composition with some variations in Si-Al-Mg and K, which together with magnetite textures indicate that the magnetite types share the same magmatic-hydrothermal origin with post-Cu-Au-mineralization processes (dissolution/reprecipitation) recorded in Mgt III. The sulfur isotope (δ34S) data for chalcopyrite (1.30-3.35‰), pyrrhotite (0.88-1.98‰), and pyrite (1.70-5.04‰) associated with magnetite I and II are consistent with a magmatic-hydrothermal sulfur source at Salobo, with minimal or no external sulfur contributions. A small isotopic gradient in chalcopyrite (ccp1: 1.56‰; ccp2: 2.73‰) indicates sulfide formation by a reaction of an oxidized Cu-rich fluid with co-precipitating or previous sulfides. Our data could suggest that magnetite precipitation at the early magmatic-hydrothermal stage triggered the sulfate reduction by ferrous iron oxidation (sulfur disproportionation) resulting in the classic IOCG mineral association of chalcopyrite+magnetite described at the Salobo deposit for the first time in this contribution. Therefore, the main mineralization event in the Salobo deposit could be older than described before (~2.5 Ga), probably coeval with similar IOCG deposits in the CMP related to the Neoarchean magmatism. Subsequent fluid-rock processes responsible for remobilization-recrystallization of magnetite and Cu-sulfides resulted in the distinctive assemblage of bornite-digenite-chalcocite.
Mafic magmatism and Sb mineralization: geochemical insights from the Central Iberian Zone, Spain

Héctor R. Campos Rodríguez, Eric Gloaguen, Anthony Pochon, Giada Iacono-Marziano, Valentin Mollé
ISTO, UMR 7327, Université d’Orléans, CNRS, BRGM, Orléans, France
Pablo Higueras, Saturnino Lorenzo, José María Esbri
Instituto de Geología Aplicada & Departamento de Ingeniería Geológica y Minera. E.I.M.I. Almadén, Universidad de Castilla-La Mancha, Almadén (Ciudad Real), Spain

This work presents the preliminary results of geochemistry of mafic intrusions (sills) and their relationship with antimony mineralization in the Central-Iberian Zone, located in the Iberian Variscan Belt. Two different areas were studied, the Almadén (Al) and the San Antonio (SA) areas. Whole rock geochemistry analyses show a difference between SA and Al dolerites. The first fall into the classical basalt field, whereas the second fall into the alkali basalt field according to the Zr/TiO$_2$ vs Nb/Y diagram. Primitive mantle normalized diagrams display high negative anomalies in Rb, K for both SA and Al. High positive anomalies for both areas in Cs, Pb and Li can be observed. All samples are depleted in HREE and enriched in LREE. Lead anomalies could be associated with assimilation of country rocks, especially marine sediments, this anomaly is also related to subduction processes. Negative anomalies in K could be associated with the presence of phlogopite in the source. Rare Earth Elements contents are compatible with the presence of garnet in the source and low degree of partial melting, this is consistent with the correlation between La/Sm vs Gd/Yb and La/Sm vs Rb. Trace element ratios such as Th/La (0.10 for SA and 0.09 for Al) suggest an enriched mantle source. Some of these mafic intrusions were collected near antimony mineralization whereas the others are located at distance but in the same swarm of mafic sills. A spatial and genetic link between Sb mineralization and mafic magmatism has been proposed in other parts of the Variscan Belt, especially in the Armorican Massif. The source of the Sb mineralization could be related to an enriched mantle with crustal contamination. The geochemical link between mafic magmatism and Sb mineralization, and their source in the Central Iberian Zone is still a matter of study.
Chromitite-associated PGE-(Ni-Cu) mineralization in the Lower Zone of the northern Bushveld: new insights from Zwartfontein

Kate Canham, David A. Holwell
University of Leicester

Iain McDonald
Cardiff University

Andy Lloyd
Anglo American South Africa

The northern limb of the Bushveld Complex is one of the Earth’s most important resources of platinum-group elements (PGE), along with significant Ni, Cu and Co, hosting the world class Platreef deposit within Critical Zone stratigraphy. In addition, the Lower Zone of the northern limb contains several other occurrences of PGE, such as the Volspruit Ni-Cu-PGE sulfide deposit and PGE mineralization associated with the Upper and Lower chromitite, both of which are located in the southern part of the limb, where thick Lower Zone sequences are present in the Volspruit-Grasvally area. We have also identified two PGE-rich chromitite horizons, and in places, a base-metal sulfide (BMS) zone within the Lower Zone in the Zwartfontein area. Downhole geochemistry indicates these horizons can be traced for considerable distance along strike and down dip from Zwartfontein.

With the exception of the Volspruit-Grasvally area, the Lower Zone of the northern limb remains poorly understood, with isolated ‘satellite’ bodies once thought to be the extent of the Lower Zone. In more recent years it has been recognized that Lower Zone rocks are variably developed beneath most of the Critical Zone and as such, characterization of any marker horizons can aid in exploration. This first mineralogical study of chromitites in the Zwartfontein Lower Zone reveals, an upper chromitite with PGE and a lower chromitite with PGE+BMS, which in places is underlain by a BMS-only layer. The upper chromitite is sulfide poor, with PGE arsenides (54% by area) and PGE sulfides (27%). Whilst the lower chromitite contains 1-4% BMS, largely pentlandite (up to 72%), with lesser chalcopyrite and pyrrhotite+/-pyrite, PGMs are dominantly Pt-Pd tellurides and bismuthides (70%). This ongoing study integrates mineralogical textures, in situ sulfide compositions and PGM studies, to unravel the syn- and post-magmatic (hydrothermal) processes involved in this Lower Zone episode of Bushveld metallogenesis.
Trace element composition of chalcopyrite as a tool for deposit type recognition: a machine learning approach

Enzo Caraballo, Georges Beaudoin
Département de géologie et génie géologique, Université Laval, Quebec, Canada

Sarah Dare
Département des Sciences Appliquées, Université du Québec à Chicoutimi, Quebec, Canada

The aim of this study is to establish trace element compositional criteria for the discrimination of chalcopyrite as a function of deposit types using machine learning classifiers. Samples (n = 323) from a wide range of representative, worldwide ore mineral deposits (n = 137) from magmatic (Ni-Cu sulfides and reef-type PGE) and hydrothermal systems (volcanic massive sulfides, orogenic gold, epithermal gold, iron oxide copper-gold, porphyry, red beds, skarn and sedimentary exhalative) were studied. Thirty-six trace elements were analyzed by LA-ICP-MS and multi-element diagrams show similar patterns for both magmatic and hydrothermal chalcopyrite. Therefore, the dataset, of 1888 chalcopyrite grains and 14 elements (<50% of censored values), were center-log ratio transformed and investigated with univariate (boxplots), bivariate (correlation, binary diagrams) and multivariate statistical methods. Silver, Bi, Co, Ga, In and Sb are enriched in chalcopyrite from hydrothermal deposits, whereas Ni, Te and Zn are higher in those from magmatic systems. Binary diagrams of Ni vs Ga, Ga vs Zn, and to a lesser extent ternary diagrams of Ni-Sb-Ga and Ni-Se-Ga, discriminate between chalcopyrite from magmatic and hydrothermal systems. However, chalcopyrite from orogenic and epithermal gold deposits overlap significantly with magmatic samples. Therefore, three machine learning classifiers, Random Forest (RF), K-Nearest Neighbors, Artificial Neural Network (ANN), and one supervised classification method (partial least square-discriminant analysis), were built using 80% of the dataset as training samples and tested using cross validation for performance in classification by deposit type. Among these classification models using geochemical variables and 9 classes (deposit types), RF and ANN show the highest performances (Kappa 0.90 and 0.70, respectively) with Se, Ga, Sn, In and Ni as the variables that contribute significantly to classification. Random Forest correctly classified 92% of the test data correctly, demonstrating that this model could be a reliable tool for discrimination of chalcopyrite for mineral exploration.
Stochastic uncertainties due to training deposits for data-driven mapping of mineral potential: challenges and a proposed solution

Emmanuel John M. Carranza
University of the Free State, Bloemfontein, South Africa
University of KwaZulu-Natal, Westville, Durban, South Africa

Mohammad Parsa
University of New Brunswick, Canada
University of Kurdistan, Sanandaj, Kurdistan, Iran

Each mineral deposit, even though belonging to a deposit type, is unique. Mineral deposits of a certain type bear striking similarities as well as differences due to variations in local geological settings within a metallogenic province or a mineral district. It follows that deposit locations show inherent differences in geochemical, geophysical, and geological signatures. Such differences in signature can be considerable, however, such that using deposit-type locations as training data impart stochastic uncertainty into data-driven mapping of mineral potential. In this presentation, to quantify this uncertainty and to alleviate its effect on exploration targets outlined by data-driven mapping of mineral potential, we apply an ensemble methodology that combines bootstrapping and naïve Bayes classifiers. The proposed methodology is demonstrated to delineate exploration targets for skarn-type Cu deposits in the Azerbaijan–Alborz magmatic belt (Iran). The predictive mineral potential model (denoted as modulated model) of the study area derived by the proposed methodology outperformed the one (denoted as ordinary model) derived using a single naïve Bayes classifier. In particular, the modulated model has higher AUC–ROC than the ordinary model, and the modulated model has lower type I and total errors compared to the ordinary model. Thus, results indicate that the proposed methodology is efficacious. However, it needs further testing in other areas where stochastic uncertainty is an important issue in data-driven mapping of mineral potential.
Gravimetric survey in the Alto do Sobrido and Ribeiro da Serra mines, Portugal

Ana Carvalho, Ricardo Ribeiro, Alexandre Lima
Department of Geosciences, Environment and Spatial Planning, Faculty of Sciences, University of Porto
Institute of Earth Sciences (ICT), Pole of University of Porto, Porto, Portugal

Rui Moura
Department of Geosciences, Environment and Spatial Planning, Faculty of Sciences, University of Porto, Porto, Portugal
INESC TEC, CRAS, Superior Institute of Engineering of Porto (ISEP), Porto, Portugal

Eric Gloaguen
ISTO, Université d’Orléans, CNRS, BRGM, Orléans, France

The Alto do Sobrido (AS) and Ribeiro da Serra (RS) mines are old Sb-Au exploration mines located in the western flank of the Valongo Anticline. A gravimetric survey was performed along with a larger campaign done for the AUREOLE project. The objective was to attempt to find a connection between the mineralization and the granites that occur at depth.

This survey was performed with a higher density of measurements in the center, where the mines are located, and a lower density in the peripheral areas. The equipment we used was a Scintex CG-5 Autograv and a Stonex S850A differential GPS.

With the processed data we obtained a Complete Bouguer Anomaly (CBA) and with the data from the larger campaign we obtained the Regional Anomaly (RA). Subtracting the RA from the CBA, we acquired a Residual Anomaly. The negative anomalies appear around the old mine workings, to the SW and NE, and close to the AS mine, while the positive anomalies occur very near the RS mine, and to the NW and SE of the mine workings.

Research by previous workers suggests a regional spatial correlation between Sb-Au mineralizations and the post-orogen granites in the Dúrico-Beirão Belt, where the AS and RS mines are located. A previous work also acquired data that suggests a genetic connection between the mineralization and the non-outcropping granites.

With this we propose the hypothesis that the negative anomalies observed could correspond to a granitic source for the hydrothermal fluids that gave origin to the mineralization of these mines. Thus, a 2D model with an associated low fit error was produced from a section, using the mapped lithologies of the area and introducing a granite at depth in the location of the negative anomalies.
The controls on the formation of porphyry copper deposits derived from crustal magmatic systems in arc settings have been a matter of debate for decades. Yet, the factors that modulate their sizes remain an open question. If the size is a matter of time, high-precision petrochronology could shed some light on the potential for certain magmatic systems to form small or giant deposits. We apply these tools to the Jurassic composite Yerington batholith (Nevada, USA) and their associated porphyry dikes, which formed several mineralized centers. High-precision zircon U-Pb CA-ID-TIMS dates show a continuous crystallization trend from the McLeod quartz-monzodiorite to the porphyry dikes, with an early volcanic event coeval with the former. Hafnium isotopic signatures remain invariable for all plutons and porphyries, advocating for a common magmatic source. Zircon trace element compositions support a continuous evolution from a less evolved magma towards a more granitic one, with decreasing Ti-in-zircon temperatures. Titanite petrochronology show similar trends for slightly lower crystallization temperatures. Importantly, zircons in porphyry dikes from different mineralized centers differ in their age spectra and trace element signatures. These new data indicate that porphyry dikes rooting the Ann Mason and the McArthur mineralized centers were extracted from different areas and depths and at different times during crystallization of their source pluton. In the McArthur porphyries, more evolved trace element compositions with lower Ti-in-zircon temperatures show that they could have been derived from a more differentiated and cooler magma, extracted deeper within the crystallizing Luhr Hill granite. Less evolved compositions and slightly higher zircon crystallization temperatures in the Ann Mason porphyries indicate an earlier, hotter source within the pluton. These observations advocate for the conception that porphyritic dikes can be derived from a cooling magma body at different stages and places during its evolution, which could impact their mineralizing potential.
Will there be enough metals for the energy and digital transitions?

Michel Cathelineau  
CNRS, CREGU, GeoRessources, LabEx RESSOURCES21, OSU Otelo, Université de Lorraine, Nancy, France

Agnes Samper  
LabEx RESSOURCES21, Université de Lorraine, CNRS, INRA, OSU Otelo, Nancy, France

The energy and digital transitions will consume an extensive range of metals (“rare metals” REE, Li and base metals (Cu)), the sufficiency of which is in question. With the concept of ore reserves often challenging to handle, too many simplistic calculations have led to alarmist projections diffusing largely the idea of resource depletion, through the concept of a “peak metal” similar to “peak oil”. However such a statement makes little sense. A proven mineable reserve corresponds to the tonnage of metal of an ore deposit, demonstrated by drilling data and subsequent numerical modeling, with more than 90% probability. All these exploitable resources are calculated with a “cut-off grade” indicator representing the part of ore within the “waste rock”, i.e. the lowest acceptable grade above which a rock formation is considered an economically mineable ore.

In the 1970s, Skinner introduced the concept of a “geological barrier” existing between exploitable ores and other common rocks. However, an exploitable reserve is not a fixed figure but depends on the price of commodities and associated specific exploitation costs linked to mines’ locations or to the technicalities of extraction and processing. The generalization of depletion calculations is therefore hampered by the heterogeneity of cut-off grades for a same metal.

Improvement in mining techniques has brought down values and cut-offs. Cut-off grades also vary accordingly to the stock market, which is primarily dependent on global demand. Technical innovation and demand are thus easing up the profitability of new mining locations situated towards more remote pristine areas, deeper, or closer to urban centers: this leads us to the paradox of developing more sustainable mining techniques into more complex locations in terms of Environmental, Social and Governance considerations, turning orebodies into more complex systems.
Heavy rare earth element potential of the Entia Pegmatite Field, Central Australia

Bénédicte Cenki, Jonas Nollo, Fleurice Parat
Géosciences Montpellier, Université de Montpellier, Montpellier, France

Patrice F. Rey
School of Geosciences, Sydney University, Sydney, Australia

Rare Earth Elements (REE) are crucial for the transition to a low-carbon society. The concentration of incompatible elements is the result of a long process of crustal differentiation after several orogenic cycles involving partial melting. However, the processes leading to their concentration into economic deposits are still poorly understood. Primary deposits for REE resources worldwide are mainly located in carbonatites and alkaline igneous rocks. However, pegmatites and their hydrothermal-metasomatic expression located within metamorphic terranes may also be important resources. An example for this type is the recently discovered Nolans Bore deposit in Central Australia. In the same area, other REE-bearing pegmatites have been identified in the Entia Pegmatite Field (EPF) in the Harts Ranges.

In order to better understand the mechanisms that create REE deposits in a metamorphic context and evaluate the EPF’s potential, we have studied pegmatites that cross-cut the orthogneiss from the Entia metamorphic dome which formed during the Alice Springs Orogeny. Detailed petrological, mineralogical and geochemical analyses have highlighted the presence of at least four different types of pegmatites: i) allanite-bearing, ii) amphibole- pyroxene-plagioclase-bearing, iii) garnet-bearing and iv) K-feldspar-mica-bearing. These pegmatites are peraluminous and most likely share a similar lower crustal source but differ in their differentiation processes and interactions during emplacement in the upper crust. Apatite REE profiles are strikingly flat and generally enriched (up to 500,000 times chondritic values) indicating that these may be potential resources of light and heavy REE. In addition, negative anomalies in Nb, Ta and Y in most rock forming minerals may point to the presence of an unusual accessory mineral like Y-samarskite in the source. Unravelling the formation of these unusual rocks will shed a novel light on the diversity and complexity of pegmatites that may form when the crust melts.
Hydrothermal systems of the Taupō Volcanic Zone (TVZ) are considered present day analogues of low-sulfidation epithermal ore deposits. Magmatism, tectonism and hydrothermalism are interrelated but the source of metals in the fluids is difficult to assess. We have undertaken a comparative study in the TVZ between two high gas active geothermal systems (Ohaaki and Rotokawa) and the fossil (~0.6 Ma) magmatic-hydrothermal system of Ngatamariki and its porphyry copper style hydrothermal halo. The current hydrothermal system at Ngatamariki is overprinting the fossil magmatic-hydrothermal system.

The active systems studied here have anomalous concentrations of Au (>1 ppb), As (>10 ppm) and Sb (>1 ppm) in whole-rock samples from depths shallower than 1,500 m (excluding the surface features), but only at Ohaaki are significant Au anomalies (>100 ppb) common. Arsenic, Sb and Au are enriched in rocks toward the surface in both fossil and modern hydrothermal systems, slightly positively correlated with sulfur, reflecting the bisulfide (HS-) complexation of these species. This is consistent with boiling as the principal mechanism responsible for the precipitation of these metals and metalloids.

Only the Ngatamariki rocks, altered by the magmatic-hydrothermal event, are enriched in Ag. Above the shallow Ngatamariki fossil intrusion, the altered rocks are also enriched in Cu, Te, Zn, Pb, Se, Bi and Mo. Therefore, the chemical zoning of altered rocks within the present-day geothermal systems is profoundly different from those of the old, high-temperature magmatic-hydrothermal altered rocks above the ca. 0.6 Ma Ngatamariki intrusive complex (2 km depth) and lacks Cu, Zn, Pb, Mo, Se, Te and Bi enrichment.

There is no compelling chemical evidence in geothermal fluids or altered rock for water-chloride-rich fluids derived from shallow magmas (4-5 km), and rather we conclude that most of the TVZ geothermal systems are fed by heat conducted from deeper (>6 km) rhyolitic magmas.
Sulfur content in calcite measured using LA-ICP-MS/MS and its application in mineral exploration

Zhaoshan Chang, Shiqiang Huang, Michael Kirschbaum

Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado, USA

Trace amount of sulfur in minerals such as carbonates may be used as a vector towards sulfide orebodies, and it may significantly extend the haloes around orebodies to farther locations for deposits hosted in carbonates or located below carbonate beds. The current methods for determining the sulfur content of a mineral are mainly electron microprobe and single quadrupole ICP-MS (Inductively Coupled Plasma – Mass Spectrometry). Both methods have high detection limits (DL), which limits the applications. For example, the sulfur DL for microprobe analysis is typically >200 ppm. For single quadrupole ICP-MS, the DL for sulfur is also high, ~70-80 ppm for glass and ~200 ppm for calcite, due to the severe interference from oxygen dimers (e.g. $^{16}\text{O}^{16}\text{O}^+$ interferes on $^{32}\text{S}^+$) resulting in high $^{32}\text{S}$ background.

With the new generation triple quadrupole ICP-MS, or ICP-MS/MS, it is now possible to minimize the oxygen interference on sulfur, thereby significantly reducing the sulfur detection limit. In this study using a Resolution-SE laser system and an Agilent 8900 ICP-MS QQQ at the LA-ICP-MS lab, Colorado School of Mines, we demonstrate that sulfur detection limits of glasses and calcite can be reduced from ~70-200 ppm under single quadrupole mode to ~3-10 ppm under MS/MS-O2 mode, while the analysis of other elements is not significantly affected. As an example of the geological application, preliminary results show that the calcite in early veins in the Jordan and Commercial Beds west of the Bingham porphyry Cu-Au-Mo deposit, Utah, has lower S away from the deposit. The sulfur content is up to ~800 ppm near the orebody, decreases to ~90 ppm at ~5 km distance, and remains at this level to ~10 km distance. Such a trend in the sulfur content of vein calcite may be used as a vectoring tool in exploration.
Olivines and Cr-spinels from the Noril’sk-1 deposit: compositional features and petrological implications

Ivan F. Chayka, Vadim S. Kamenetskiy
Institute of Experimental Mineralogy RAS (Russia)
V.S. Sobolev Institute of Geology and Mineralogy SB RAS (Russia)

Andrey E. Izokh, Valery M. Kalugin, Liudmila M. Zhitova, Marina P. Gora, Artem Ya. Shevko
V.S. Sobolev Institute of Geology and Mineralogy SB RAS (Russia)

Gennady I. Shvedov
School of Mining, Geology and Geotechnology, SFU (Russia)

Noril’sk-type deposits, located within several differentiated ultramafic-mafic intrusions (Noril’sk-1, Talnakh, Kharaelakh and certain smaller bodies) of the Siberian large igneous province (LIP), are supergiant resources of Cu-Ni and PGE ores. Explored orebodies comprise massive and disseminated sulfide ores, which are believed to have originated during silicate-sulfide immiscibility in trap magmas. However, within the upper zones of these intrusions there are rocks ("sulfide-poor ores"), anomalously enriched in Cr-spinel and platinum group elements (PGEs) with elevated PGE/Cu-Ni-sulfide ratios, which resemble reefs of Bushveld and Stillwater intrusions. Although these rocks were attested as economic PGE deposits, they are poorer studied than the other types of ores and there is no consistent model for their formation. In this report, which is part of a complex study of the Noril’sk-1 sulfide-poor ores, we discuss compositional features of olivine and Cr-spinels from sulfide-poor and disseminated sulfide ores from this intrusion and compare them with their counterparts from the overlying volcanics. Cr-spinels of the Noril’sk-1 intrusion underwent re-equilibration with silicate matrix, while compositions of olivine imply silicate-sulfide immiscibility followed by re-equilibration of olivine with high-Ni sulfides. We deduce that the considered ore types were formed from high-Ni magmas, compositionally close to picrobasalts of the Gudchikhinskiy formation. Olivine-Cr-spinel equilibrium varied from 1150 to 1240 °C for both Gudchikhinskiy formation and "sulfide-poor" ores. Oxygen fugacities \( \log_{10}(f(O_2)) \) estimated from olivine-spinel equilibria and Fe\(^{2+}/Fe^{3+} \) ratios in Cr-spinel are: -7.5 to -9 for disseminated sulfide ores; -7 to -12 for "sulfide-poor ores" and -9 to -9.8 for the Gudchikhinskiy picrobasalts. Overall, the study reveals physiochemical differences between disseminated sulfides and sulfide-poor ores and implies that those could have been formed from different magma pulses. Differences in redox conditions should be considered when discussing the origin of the high PGE/sulfide ratio (sulfide depletion) of the "sulfide-poor ores".
$ or $$$$? Estimating the size of porphyry Cu deposits early on

Cyril Chelle-Michou  
Department of Earth Sciences, ETH Zürich, Zürich, Switzerland

Bertrand Rottier  
Département de Géologie et Génie Géologique, Université Laval, Québec, Canada

Theoretical, conceptual, technical and analytical advances over the last century have enabled researchers not only to develop and refine models for the formation of porphyry copper deposits, but also to develop cost-effective exploration methods to identify new deposits. However, once a new orebody is identified, it requires extensive drilling campaigns and massive investments to quantify its metal content. This is associated with increasing economic risks and social and environmental impacts, that are magnified by the current need to search for increasingly deeper orebodies (under cover). In order to mitigate such risks, it would be advantageous to be able to determine (even coarsely) the size of the newly discovered deposit as early as possible during exploration.

However, while commonly advocated magmatic-hydrothermal processes and their associated fertility indicators may indeed pinpoint toward the formation of porphyry deposits, they fall short in explaining the size diversity of porphyry deposits of the world that ranges over five orders of magnitude in copper content. Here we show that the chemical factors of magmatic systems play a secondary role compared to the physical factors on the fertility of such systems. We propose that the magma intrusive flux and timescales in tandem with the thermo-mechanical conditioning of the upper crust by the precursor magmatic activity may provide clues to some of the key factors controlling the size of porphyry copper deposits. Further we explore possible ways to assess this ‘physical fertility’ from the rock record by combining cutting edge analytical methods and advanced numerical models.

Fingerprinting the formation of Sn and W (±Mo) mineral systems and developing mineral exploration tools

Yanbo Cheng  
Minerals, Energy and Groundwater Division, Geoscience Australia, Symonston, Australian Capital Territory, Australia

This study examines the in-situ trace element composition of zircon and cassiterite, geochronology, bulk rock geochemical and zircon Hf isotopic features of volcanic-intrusive rocks from several prominent Sn and W (±Mo) districts. Thereby, their potential as new exploration tools have been revealed.

Cassiterite is an important Sn ore mineral in nature and capable of incorporating a wide range of trace elements, hence the chemistry of cassiterite can provide insight on conditions of crystallization under hydrothermal conditions, which could be helpful for developing tin ore exploration models. A set of cassiterite samples from different mineralization environments were analyzed by LA-ICP-MS, and Zr/Hf and Ti/Zr ratios of cassiterite have shown potential as a broad tool for vectoring toward a tin mineralized intrusive systems.

This study also investigates the redox characteristics of the granites related to W and Sn mineralization, and further discusses the magmatic controls leading to the formation of Sn, W, porphyry Cu-Au, porphyry Mo and granite-related W-Mo deposits. Results suggest that Ce<sub>n</sub>/Ce<sub>n</sub>* and Eu<sub>n</sub>/Eu<sub>n</sub>* ratios are useful metal discriminators for porphyry Cu-Au, via porphyry Mo, Mo-W, W-dominant, to Sn-dominant mineral deposits. When combined with Mo/W tonnage ratios, the Ce<sub>n</sub>/Ce<sub>n</sub>* ratio of zircon can be a useful tool for determining the style of Mo-W mineralization.

To discern differences between “fertile” and “non-fertile” igneous rocks associated for Sn and W (±Mo) mineralization, and reveal the genetic links between coeval intrusive and extrusive rocks, this study integrated multiple datasets from contemporaneous plutonic and volcanic rocks from the Herberton Sn and W (±Mo) mineral field. The outcomes display the geochemical differences between these igneous rocks, which therefore are considered to be helpful for regional Sn and W exploration.
Carbonatite melt as a travel agent for magmatic sulfide liquid: nature vs experiments

Maria Cherdantseva, Marco Fiorentini
Centre for Exploration Targeting, The University of Western Australia, Perth, Western Australia, Australia

Michael Anenburg, John Mavrogenes
Research School of Earth Sciences, Australian National University, Canberra, Australia

The problem of transportation of dense metal-rich sulfide liquid by magma from the mantle across the lithosphere has been discussed in the magmatic sulfide literature for decades. Its resolution may have profound implications in our understanding of the global metal and sulfur cycles and provide insights into the genesis of extremely valuable magmatic Ni-Cu-PGE deposits. Initially, it was suggested that the metal-rich sulfide budget in the mantle had to be exhausted during partial melting to be efficiently transported by rising magmas. However, results from experimental work and evidence from numerous natural examples indicate that alternative mechanisms may play a crucial role as well. Recently, the hypothesis that the transportation of sulfide liquid could be facilitated by the presence of magmatic volatile phases has gained credit given the near-ubiquitous association between metal-rich sulfides and water- and carbon dioxide-bearing minerals in deposits emplaced at variable depths in the crust. Recent hypotheses based on the documentation of this observed spatial relationship emphasise the adherence of volatiles to sulfide liquid and the consequent importance of compound bubbles. Depending on the depth of the emplacement, it was proposed that the volatile phase can be represented by a CO₂ supercritical liquid, an aqueous phase, or by the occurrence of gas bubbles that tend to stick to sulfide liquid decreasing its buoyancy and facilitating its transport. Our detailed study of a number of selected mineralized mafic-ultramafic intrusions shows that the mineral assemblage associated with sulfides is not only enriched in volatiles but displays a characteristic trace element and isotopic signature that is typical of carbonatite liquids. We present here natural and experimental evidence of the immiscible behavior of carbonatite, silicate and sulfide liquids, providing new insights into the composition of the envelopes that surround sulfide globules and their ability to facilitate their ascent through the lithosphere.
LA-ICP-MS mapping of sandstone from the Proterozoic Athabasca Basin (Canada) – implications for REE and unconformity-related U mineralization

Guoxiang Chi
Department of Geology, University of Regina

Eric Potter, Duane Petts, Simon Jackson
Geological Survey of Canada

Haixia Chu
China University of Geosciences (Beijing)

The Proterozoic Athabasca Basin in northern Canada hosts a number of world-class unconformity-related uranium deposits, many of which contain significant concentrations of rare earth elements (REE). The basin also hosts hydrothermal REE mineralization (Maw zone). The source(s) of the metals have been a subject of scientific debates, with two contrasting hypotheses: basin- or basement-derived. In a recent study, we documented U- (up to 27 ppm) and REE-rich diagenetic fluids in fluid inclusions from quartz overgrowths on detrital grains in sandstones of the Athabasca Basin. These results indicate the basinal brines were rich in metals, however, the detrital sources of metals remain unclear. Potential U and REE sources in the sandstones include: accessory minerals containing REE and U, or adsorption on clay minerals and Fe-(Ti) oxides. Laser ablation – inductively coupled plasma – mass spectrometry (LA-ICP-MS) mapping of quartz arenite indicates that most elements (except Si) are enriched in the interstitial materials compared to the detrital quartz. Elements that are strongly enriched in interstitial minerals include Al, K, Li, Fe, Sr, Y, Zr, Ba, La, Ce, Eu, Dr, Hf, Lu, Pb, P, U and Th. Elements that are weakly enriched in interstitial minerals include B, Na, Mg, Ca, Mn, Ti, Cr, Ni, Cu, Zn, Bi and S. Poor correlations between U and Al, Na, K, Fe and Ti suggest that clay minerals and Fe-(Ti) oxides are not the dominant hosts to U and REE. The strong positive correlation between U and REE (including Y), Th, Sr and P, and moderate correlation between U and Zr, suggest that detrital monazite and apatite may have been more important U contributors than zircon. More micro- to nanoscale studies are required to determine the original U and REE contents in the sediments and the processes in which these elements were extracted by basinal brines.
PRISMA hyperspectral remote sensing for exploration of Co-Ni deposits: example from the Punta Corna cobalt project (Piedmont, Italy)

Rita Chirico¹, Nicola Mondillo¹, Carsten Laukamp², Giuseppina Balassone¹, Diego Di Martire¹, Alessandro Novellino³, Simone Zanin⁴

¹University of Naples Federico II, Naples, Italy
²CSIRO Mineral Resources, Kensington, Western Australia, Australia
³British Geological Survey, Keyworth, United Kingdom
⁴Alta Zinc Ltd, Via Roma 492, Oltre il Colle, Italy
⁵Natural History Museum, London, United Kingdom
⁶INVG-OV, Naples, Italy

This work comprises a multi-stage workflow, including both hyperspectral ground and satellite-based data, mainly using the recently implemented PRISMA spaceborne sensor (Italian Space Agency – ASI), with a view to tuning new methods for supporting safer and more sustainable decisions for the mineral exploration processes. The Punta Corna Cobalt Project, under investigation by Alta Zinc Ltd, crops out between the Arnàs and the Ala valleys, located in the Western Alpine belt at an average altitude of 2600 m. The deposit is defined by several hydrothermal polymetallic veins characterized by Fe²⁺-rich carbonates and associated Co-Ni mineralization, hosted by E–W-trending, subvertical post-metamorphic structures that are crosscutting metaophiolitic rocks (metabasites in greenschist–facies and, locally, calcschists). PRISMA is a hyperspectral sensor, providing imagery in a continuum of 240 bands in the visible to near infrared (VNIR) and shortwave infrared (SWIR) wavelength regions of the electromagnetic spectrum (400-2505 nm) at a spatial resolution of 30 m. The spectral signature of host rock samples and alteration minerals has been analyzed and used as precondition for image interpretation. For this, the spectral diagnostic signatures of each target mineral phase guided the production of mineral distribution maps, which were based on combinations and ratios of bands collected by PRISMA. A PRISMA Level 2D image has been processed for the detection of the hydrothermal alteration areas by producing Ratio Maps showing the MgOH-group and Fe²⁺-iron-bearing minerals distribution, mapped by means of two band ratios: (B141+B166)/(B149+B150) (B141=2268; B166=2449; B149=2327; B150=2335, values in nm) and (B58VNIR+B71)/(B12+B31) (B58VNIR= 919; B71= 1657; B12= 1029; B31= 1229; values in nm), respectively. The results show that a multi-scale optical remote sensing approach, integrated with geomorphological and field data, represents a feasible tool for mapping the zonation patterns associated with Co-Ni-bearing hydrothermal vein systems and for supporting the ore exploration phases.
Post-subduction metallogenesis in upper crustal Au-Te deposits: insights from Tuvatu, Fiji

Rose Clarke, Daniel Smith, David A. Holwell  
*University of Leicester*

Stephen Mann  
*Lion One Metals*

Jon Naden  
*British Geological Survey*

Post-subduction epithermal Au-Te deposits have been studied since the early 1900s owing to world-class Au tonnages. Interest was renewed at the turn of this century due to their abundance of energy-critical elements, most notably Te. Mineral systems models proposed at the time centered on mantle sources and upper crustal deposits. These have subsequently evolved into trans-lithospheric models linking lower to middle crust magmatic sulfide mineralization to upper crustal porphyry-epithermal mineralization. This ‘continuum’ model proposes Cu-Au-Te-rich magmatic sulfides in the middle crust redissolve into ascending melts that form alkalic porphyry Cu-Au-Te and epithermal Au-Te deposits. Recently, CO₂ has been proposed as a physical driver for these sulfides and their metal cargoes.

Yet, evidence of the continuum model is lacking in the upper crust, owing to degassing, overprinting and wall-rock interactions. Tuvatu, Fiji, provides an example of alkalic-type epithermal Au deposits to test models, whereby the tectonics are relatively simple, and the mineralization is hosted in monogenetic veins. Regional magmatic rocks across Fiji imply that source controls may require both an enriched mantle and lower crustal cumulates even in this geologically ‘simple’ arc. Detailed mineralogical mapping has identified a spatial association between calcite and Au-telluride minerals in veins and at Tuvatu, Pt- and Pd-tellurides for the first time.

This study allows some key processes to be constrained and provides an insight into linkages between the mantle and upper crustal deposits in post-subduction environments. The associations here, and elsewhere globally, between Au-Te mineralization and alkalic magmatism in post-subduction terrains point to a common genetic heritage. Within these systems, various processes and features may contribute to fertility, including partial melting of enriched sources; the role of semi-metal melts in transferring precious metals, with possible enhancement by CO₂; and the potential for high pH fluids to facilitate metal transport and precipitation in the vein systems.
Threats to supply security of critical elements are often due to inadequately established value chains, with many being sourced as by-products. Ironically, by-products are attractive to use when technologies are designed, as they are often low-cost and have decoupled supply and demand, though this also enhances criticality.

Improving access to these elements requires broadening supply bases. This can be done by improving the understanding of new resources, or increasing the resource intensity of existing mines to encourage the mining of these elements as by-products. Here we use Te, a critical element used in CdTe solar cells, as a case study to evaluate these points. At present, most Te is sourced as a by-product of Cu, via the re-processing of anode slimes from porphyry deposits. Yet, despite its rarity in the crust, Te forms more Au-bearing minerals than any other element. As such, here we consider not only current routes of Te production, but also production as a by-product of alkalic-type epithermal Au deposits. In addition to yielding world class Au tonnages, these deposits contain elevated Te concentrations. Previously Vatukoula, Fiji, an example of this deposit type, was the only direct producer of Te in the world.

This study utilizes life cycle assessment (LCA) methodologies as well as scenario analysis and carbon accounting to assess the environmental impacts of Te production, and ways to incentivize its mining via alkalic Au mining. Whilst this provides a technically feasible option, we show that scarce data makes proper analysis challenging. We also show that economics alone are unlikely to drive production of Te via Au, and even when allowing Te to offset some of the negative impacts of Au (e.g. CO₂ emissions), incentives are not strong enough. Yet, increasing resource intensity likely remains a positive action, which subsidies could assist in enabling.
Geology and mineral chemistry of alteration minerals at the Mt Eliott, Corbould and SWAN deposits, NW Queensland, Australia

Jonathan C. Cloutier, Jeffrey A. Steadman, Max Hohl, David R. Cooke
CODES (Centre for Ore Deposit and Earth Sciences), University of Tasmania, Hobart, Tasmania, Australia

Iron oxide copper gold (IOCG) deposits are associated with large alteration halos of contentious origin. From a mineral exploration perspective, these alteration halos can preserve geological, mineralogical and geochemical information that can be used to vector toward the mineralized centre. In this study, we present a new deposit scale 3D geological model and a detailed paragenesis of the alteration minerals from the SWAN, Mt Elliott and Corbould deposits, which are located in the Eastern Fold Belt of the Mount Isa Inlier, Northwest Queensland, Australia, in order to characterize the variation in trace element abundance obtained by LA-ICP-MS with distance to the ore shells.

The new geological model reveals that the mineralization is spatially related to a mafic intrusion. The mineralization at Mt Elliott and Corbould is associated with an apophysis of the intrusion hosted in quartz mica schist, whereas the SWAN mineralization flanks the same mafic intrusion at depth to the SE and is hosted in highly altered marble. The paragenetic sequence at SWAN consists of five alteration stages: 1) sodic, 2) prograde, 3) early mineralization, 4) potassic, and 5) late mineralization. The prograde alteration stage is associated with an anhydrous, reduced and high temperature mineral assemblage dominated by pyroxene, magnetite, titanite and apatite, whereas the Cu-Au mineralization stages are associated with a lower temperature assemblage of amphibole, pyrite, chalcopyrite, anhydrite, epidote, chlorite and calcite concordant with the onset of hydrothermal alteration by an oxidized fluid.

Trace element composition of all alteration minerals studied (pyroxene, magnetite, apatite, amphibole, pyrite, epidote and chlorite) show a relationship to the distance with the 0.25% Cu Eq surfaces up to 600 m away (sampling limit). This relationship shows that mineral chemistry can be used as an exploration tool for IOCG deposits of the Cloncurry area.

Pining for an anomaly: vectoring towards mineralization using biogeochemistry

David R. Cohen
School of Biological, Earth & Environmental Sciences, University of New South Wales, Sydney NSW 2052, Australia

The value of regional geochemical mapping is well established in mineral exploration. The use of vegetation as the primary sampling media at the regional scale has, however, rarely been evaluated. 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 the Broken Hill Block, and in Cyprus. Sampling has generally focused on species of Pinus based on their capacity to take up a wide range of metals without causing toxicity to the plants. The studies have included comparisons between laboratory-based element analysis methods and portable XRF.

Strong biogeochemical responses have been found in pine needles over a range of deposit types (Au, Cu-Pb-Zn, Ni-Co) with otherwise low background values. Coherent zones with multi-element anomalous biogeochemical values are observed in areas where mineralization is buried under transported cover up to 10 m in depth. This includes both the main ore-related elements and also other mineralization related elements including W, As, Re and REEs. With the pines, the only element for which responses are typically subdued is Cu, indicating strong controls on uptake. Variations in underlying lithologies or proximity to drainages are also reflected in a number of elements, including Mn and Zn.

For many elements there is strong correlation between ICP-MS analytical values and those derived from pXRF analyses in the lab and even on raw vegetation samples in the field. In most cases simple correction factors need to be applied if ICP-MS and pXRF datasets are to be merged. Biogeochemical sampling is rapid and the sample preparation requirements similar to those for regolith materials such as soils and stream sediments.
Geological evolution of the Lihir gold deposit, Papua New Guinea

David R. Cooke, Erin Lawlis, Stephanie Sykora, David Selley
CODES, Centre for Ore Deposit and Earth Sciences, University of Tasmania, Hobart, Tasmania, Australia
Anthony C. Harris
Newcrest Mining Ltd, Melbourne Victoria, Australia

The Lihir gold deposit, Papua New Guinea, is the world’s largest alkalic low-sulfidation epithermal gold deposit in terms of contained gold (50 Moz). This Pleistocene gold deposit evolved from porphyry to epithermal-style hydrothermal activity over the past million years, with geothermal activity persisting today.

Lihir’s early hydrothermal activity produced widespread porphyry-style biotite – anhydrite – pyrite ± K-feldspar ± magnetite alteration, weak gold ± copper mineralization and abundant anhydrite ± carbonate veins and anhydrite ± biotite-cemented breccias. Several hundred thousand years ago, one or more catastrophic mass-wasting events unroofed the Lihir porphyry system after porphyry-stage hydrothermal activity ceased, causing the top of the Luise volcanic edifice to be removed instantaneously. Epithermal mineralization occurred after sector collapse, resulting in phreatic and hydraulic brecciation and veining, widespread adularia – pyrite ± carbonate alteration, and formation of multiple mineralized ore zones that were mostly localized by a network of NE- to ENE-striking faults. Pyrite-rich veins and pyrite-cemented breccias mostly contain refractory gold in pyrite, with minor free gold and precious-metal tellurides hosted in late-stage quartz veins.

A period of diatreme volcanism disrupted the Luise amphitheater during the latter stages of epithermal mineralization. The diatreme breccia complex has seven identified feeders that were controlled by the same fault array that localized gold mineralization. The diatreme complex truncated several of the epithermal ore zones and was crosscut locally by late-stage epithermal veins.

Recent geothermal activity formed a steam-heated clay alteration blanket that overprinted the near-surface refractory sulfide-rich epithermal ores. High-temperature leaching caused gold to be remobilized downward from the steam heated zone into the sulfide zone during argillic and advanced argillic alteration, producing thin gold-rich rims around pyrite grains. This recent steam-heated process produced a high-grade tabular enrichment zone immediately beneath the base of the clay blanket, producing Lihir’s erroneously named ‘boiling zone’.
LocatOre: a tool for modeling proximitor equations using multi-element mineral chemistry data

Matthew J. Cracknell, Michael Baker, Stephen Cooke, David R. Cooke, Leonid Danyushevsky, Ivan Belousov, Paul Olin
Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Tasmania, Australia

Multi-element mineral chemistry data acquired by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) are a rich source of geochemical information. These data can contain subtle geochemical signatures related to a mineral’s proximity to the heat and fluid source. For example, analyses of hydrothermal chlorite from the alteration halos surrounding Batu Hijau (Indonesia) and El Teniente (Chile) porphyry Cu deposits show a clear trend of decreasing Ti/Sr ratios with increasing distance from mineralizing intrusions.

Proximitor equations are functions that model the relationship between element concentrations in an alteration mineral and the distance to its related heat and fluid source. The coefficients for these equations can be estimated from samples where the location of the source is known. The resultant coefficients can then be applied at sites where the source location is not known to define an exploration target. Manual calculations of distance to source and modeling of source locations using proximitor equations is a time-consuming process, requiring multiple individual calculations, and is consequently often limited to a 2D surface.

LocatOre is an application, developed in the Unity game engine, that simplifies the calculation, modeling and visualisation of proximitor equations for estimating the distance to heat and fluid source in 3D. The application provides users with options to use pre-set proximitor equations for LA-ICP-MS mineral chemistry data from a range of ore deposits, minerals and elements. Users can define custom proximitor equations, subset samples and visualise the model space in 3D. In addition, tools for identifying exploration targets and exporting modeling results for use in other applications are available. LocatOre is an important new tool in the mineral explorer’s toolbox that allows for the construction of rapid and consistent interactive models for representing possible heat and fluid source locations in a prospective area.

Orogenic gold mining and exploration in the Otago Schist, New Zealand

Dave Craw
Geology Department, University of Otago, Dunedin, New Zealand

Orogenic gold was emplaced in the metasedimentary Otago Schist in two distinct pulses, in Early and Late Cretaceous, and exposed at the surface during Cretaceous-Cenozoic erosion. Historic mining yielded <0.5 Moz Au compared with >8 Moz Au produced from placer deposits in the region. Historic mining focused on shallow parts of the steeply dipping quartz vein deposits where coarse free supergene gold was easily extracted. Gold grades and particle sizes decreased below ~50 m depth, where Au was predominantly encapsulated in pyrite and arsenopyrite, and difficult to separate. The modern Macraes mine has developed in a 30 km long, shallow dipping brittle-ductile shear zone (Early Cretaceous), with >5 Moz Au produced since 1990 from a total resource of >12 Moz. Macraes has only minor quartz veins, and the ore is mostly sulfidic sheared schist with abundant hydrothermal graphite. Gold recovery was initially hindered by the refractory sulfide-hosted Au, and graphite-related preg-robbing in the cyanidation system. Introduction of fine grinding (~15 µm) and a pressure-oxidation autoclave have facilitated production from ore grades near 1 g/t Au. Bulk mining of low-grade ore, without a focus on higher-grade quartz veins, has been a key to success at Macraes. This success has in turn transformed the principal targets for regional exploration in the Otago Schist, to focus on large-scale shear zones rather than the small-scale quartz vein systems mined previously. The most prominent example is the Rise & Shine Shear Zone, a >7 km long Late Cretaceous structure located ~100 km NW of Macraes, which has been, and still is being, extensively prospected. Both Macraes and Rise & Shine systems were mined historically in their minor quartz vein components before the shear zone extensions were discovered. This approach is likely to dominate orogenic gold exploration in Otago, and possibly elsewhere, in the future.
Placer gold morphology, composition and concentration during extensive recycling, southern New Zealand

Dave Craw
Geology Department, University of Otago, Dunedin, New Zealand

Placer gold has been repeatedly concentrated, recycled and re-concentrated in southern New Zealand since initial exposure of source orogenic gold deposits in the Otago Schist in the Late Cretaceous. Past production has been >8 Moz Au, and small to medium scale mining activity has been almost continuous for 160 years. Source gold particle sizes were enhanced by supergene processes, with some growth of small (cm scale) nuggets, and downstream sorting resulted in most fluvial gold particles in 0.1 to 2 mm range, while beach placers have particles <0.1 mm). Fluvial concentrations resulted from optimisation of three principal factors: sediment supply (uplift and erosion), rainfall and stream gradients. These optimised combinations initially caused repeated reworking of sediments to concentrate gold, with only minor (1-10 km) lateral transport. Uplift and erosion of pre-existing placers during extensional and compressional tectonics through the Cenozoic resulted in creation of younger placers progressively farther downstream. Some detrital gold has been transported >200 km from primary sources in single cycles but most lateral transport involved several cycles. Gold particles became variably flattened and internally annealed during recycling and transport, and Ag was leached from up to 10 wt% down to 1-5 wt%. Annealing continued after deposition in a placer, and the oldest (Late Cretaceous) placers have gold particles almost fully annealed internally. Thin (~10 µm) overgrowths of authigenic gold formed within placers from groundwater dissolution and reprecipitation of Au, mediated by bacteria. When gold flakes reached the coast, they were concentrated in beach placers, and in windy sites the flakes have been sand-blasted to form toroids. Uplift and recycling of older beach placers returned toroidal gold to coastal fluvial environments. Linkage of placer gold to specific sources through these cycles and transformations is difficult.
As exploration progresses undercover, a clear understanding of the controls on ore shoot geometry and grade distribution is essential for focused and efficient exploration targeting. The location, orientation and grade of mineralization in the Oberon orogenic gold deposit in the Granites–Tanami Orogen is strongly influenced by rheological variability between adjacent lithologies. This differs from other large deposits within the region, where geochemical controls are considered to be paramount. The base of the host succession at Oberon is dominated by medium-grained quartz-rich sandstones and transitions upwards into fine-grained sandstones, siltstones, carbonaceous mudstones and local chert horizons. The sedimentary sequence is intruded by a semi-concordant gabbroic sill, and the entire stratigraphic package is folded about an east–west-trending, isoclinal anticline. Gold is present as coarse particles within hydrothermal veins and as inclusions within disseminated arsenopyrite. Mineralized veins occur as a network of mutually crosscutting, co-genetic, sub-vertical shear veins and as sub-horizontal extensional veins. At the deposit scale, ore shoots are located at the contact between the gabbroic sill and the sedimentary rocks. The sill margins display intense ductile deformation, whereas the adjacent siliciclastic sediments display brittle deformation and extensive hydrothermal fracture networks. The intensity of hydrothermal fracturing is most notable within the basal quartz-rich sandstones. Hydrothermal alteration is associated with extensive, disseminated, arsenopyrite-gold mineralization and abundant high-grade intercepts. Local chert horizons are associated with increased hydrothermal vein abundance and high-grade gold, yet have very low arsenic concentrations. In contrast, ductile deformation dominates carbonaceous mudstones, in which mineralization occurs as narrow, bedding-concordant, vein-poor, arsenopyrite-dominated lodes. A combination of these critical controls on the nature and location of mineralization, combined with a clear understanding of fold geometry, is a powerful exploration tool, with the ability to predict ore shoot geometry and guide deep exploration targeting.
Submarine hydrothermal systems as the shallow parts of porphyry Cu systems: the case for Brothers volcano

Cornel E.J. de Ronde
GNS Science, Lower Hutt, New Zealand
and IODP Expedition 376 Scientists

The geological record has several examples where sizeable volcanogenic massive sulfide deposits appear to have formed within submarine arc caldera volcanoes, including some that appear to be the shallow expression of porphyry Cu deposits. In 2018, a series of boreholes were drilled by the International Ocean Discovery Program into two active, but distinct hydrothermal systems at Brothers volcano of the Kermadec arc. One is magmatically-influenced and includes the Upper and Lower Cone vent sites atop volcanic cones. The other is seawater-dominated and includes the Upper Caldera, NW Caldera and West Caldera vent sites, each perched on the caldera walls. The NW Caldera site strikes for ~600 m in a SW-NE direction where numerous active and inactive chimneys occur over a ~145 m depth interval, between ~1,690 and 1,545 mbsl. Faulting has exposed an anastomosing network of metal-rich stockwork veins that occur beneath the chimneys. These veins contain up to 10.1 wt.% Cu, 5320 ppm Zn, 3580 ppm As, 740 ppm Co, 467 ppm Mo, 296 ppm Pb, >90 ppm Se, >40 ppm Te, 40 ppm Bi, 37 ppm Sb, 16 ppm Ag, 12 ppm In, >11 ppm Tl and 1.9 ppm Au. Drilling shows hydrothermal alteration of the host dacitic volcaniclastics and lavas reflects primary lithological porosity and contrasting spatial and temporal contributions of magmatic fluid, hydrothermal fluid, and seawater. Initial hydrothermal activity, prior to caldera formation, is dominated by magmatic gases and hypersaline brines. The former mix with seawater as they ascend towards the seafloor, and the latter remain sequestered in the subsurface. Following caldera collapse, seawater infiltrates the volcano through fault-controlled permeability, interacting with wall rock and the segregated brines, transporting associated metals towards the seafloor and forming present-day Cu-Zn-Au-rich chimneys. Such a two-step process exposes metals that may be associated with a deeper porphyry Cu system.

Ore-bearing fluids for VMS deposits in basaltic oceanic crust: insights from the Semail ophiolite, Oman

Larryn W. Diamond, Lisa Richter, Thomas Pettke
Institute of Geological Sciences, University of Bern, Baltzerstrasse 3, Bern, Switzerland

Hydrothermal fluids in basaltic oceanic crust are known to carry base metals that precipitate at seafloor black-smoker vents, forming volcanogenic massive sulfide (VMS) deposits. However, the origin of the ore-bearing fluids and the source rocks for the metals are debated. The oceanic crust exposed in the Semail ophiolite (Oman) contains numerous Cyprus-type VMS deposits in early MORB-type lavas and in later island-arc tholeiites and boninites, which collectively record a proto-arc volcanic sequence. The literature on such MOR to proto-arc settings proposes three contender ore-bearing fluids for VMS deposits: modified seawater that alters the deep crust to spilite (chl + alb ± act); modified seawater that alters the deep crust to epidote; and magmatic–hydrothermal fluids that exsolve from oceanic plagiogranites. To discriminate the contender fluids, we determined the concentrations of Mn, Fe, Cu, Zn and Pb in the three fluids by analyzing fluid inclusions belonging to the three rock types in the Semail ophiolite. To benchmark these fluids we analyzed the same metals in fluid inclusions in a stockwork immediately beneath a VMS deposit in Oman. The results show that epidotizing fluids contained too little Fe and Cu to form VMS deposits. Plagiogranite fluids had sufficiently high Cu contents, but mass-balance calculations show that not enough of this fluid was released from the Semail crust to explain the known mass of Cu in the deposits. In contrast, spilitizing fluids were enormously abundant and they had high base-metal contents compatible with the ore-forming fluid in the stockwork, such that they readily account for the mass of Cu in the deposits. We conclude that spilitizing fluids are the best contender for VMS ore-bearing fluids in end-member mafic crust. These findings thus contrast with those for mature volcanic arcs, where magmatic fluids are known to be major contributors of metals to VMS deposits.
Lessons from the self-organization concept for geological and ore forming processes

Sabine Dietrich
Alumna Technical University of Berlin, Germany

Geological systems in the Earth’s crust, including orebodies, commonly display rhythmic patterns such as banded formations, layered and folded structures, diapirs or cockade ores that can range in scale from just the micron, and even sub-micron-scale, up to several kilometers. The topic has been examined from a thermochemical-mechanical perspective for a long time. The concept of self-organization is here applied to mineral deposits and geological processes in general. Recognizing geological systems, mineral deposits and orebodies as ordered structures implies that they are considered as systems in which their components and properties are distributed in space and time, providing fundamental aspects to understand them. The complexity in describing connections and feedback between contributing key processes can thus be reduced, leading to an improved understanding and achievable numerical simulations.

The proof of concept was validated by examination of a recent, early diagenetic banded iron-manganese mud in an abandoned underground mine that had accumulated over 40 years. Two years of in-situ testing revealed that the self-organizing nature of the precipitated material was not only caused by fluctuations but also by interaction with redox, colloid, microbial, electrical and Ostwald-ripening processes. A genetic model for the banded mineralization was developed and successfully verified by numerical simulation. Moreover, gradients, such as concentration gradients, electric fields, and the like, as well as temperature and pressure, enabled a coupling of the ongoing processes that is spatially and temporally far-reaching.

Such thinking could allow other information about geological and ore-forming processes to be revealed, which is otherwise hidden by time, environmental conditions or by location. The long-term examination revealed that the banded iron-manganese mud forms by multiple complex processes that couple linearly and non-linearly. The colloid-like, thermo-dynamical unstable hydrated iron and manganese oxides re-organise. Primary bands restructure self-organized to secondary fine bands, at ambient conditions within a few decades.
The Vulcan IOCG prospect is characterized by a distal (>700 m) sodic alteration zone represented as pervasive albitization of host rocks, with no recorded calc-silicate minerals. In the mineralized zones as well as zones proximal to the mineralization (<300 m), the HyLogger-3 data revealed an inverse relationship between the abundance of feldspars and white mica (Al-OH feature) highlighting zones of sericitic alteration, developed in/around the hematite breccias caused by feldspar breakdown. The Al-OH (2200 nm) absorption feature within the hematite-breccias has shorter wavelengths (~2205 nm) but trends towards longer wavelengths outside of mineralized intervals (~2220 nm). The abundance of hematite breccias was efficiently mapped using a suite of the Fe$^{3+}$ absorption features in the visible near-infrared spectra. The abundance of Fe$^{2+}$-bearing minerals highlighted zones of intense chloritic alteration (+ankerite/siderite), while compositional changes of chlorite indicated Fe-chlorite dominates within the mineralized zones, however, both Fe- and Mg-chlorite is associated with the mafics of unknown age which in some zones contain sulfides.

The observed results indicate strong mineralogical similarities between the alteration in the Vulcan prospect and other deposits/prospects in the Olympic Cu-Au province. Developing an understanding of sodic, potassic and sericitic-chloritic alteration types and their relationships with mineralization in the Vulcan prospect provides important information about the space-time evolution of the IOCG system and represents valuable information about its economic potential.
Tracking the temperature and composition of hydrothermal fluids: the application of clumped O-C and strontium isotope analyses in the Irish Zn-Pb orefield

Aileen Doran, Julian Menuge
iCRAG and UCD School of Earth Sciences, University College Dublin, Belfield, Dublin, Ireland

Steve Hollis
Geological Survey Ireland, Haddington Road, Beggars Bush, Dublin, Ireland
School of Geosciences, Grant Institute, The University of Edinburgh, Edinburgh, United Kingdom

Irish-type Zn-Pb deposits are a form of carbonate-hosted, stratabound and structurally-controlled sulfide mineralization. Within the southern Irish orefield, there is a belt of regionally dolomitized Lower Carboniferous (Mississippian) marine limestones that are cut by a series of NE-SW-trending ramp-relay normal faults, known locally as the Rathdowney Trend. Several Zn-Pb sulfide deposits are located along this area, including the recently mined Lisheen and Galmoy deposits, with massive Zn-Pb occurrences generally found adjacent to normal faults. These faults acted as fluid conduits for hydrothermal fluids, facilitating mixing with cooler brines.

Dolomite formation is an important component of Irish Zn-Pb deposits, forming before, during and after massive sulfides. Regional dolomitization was crucial for later Zn-Pb mineralization, increasing the permeability and porosity of the host rocks. Later dolomitization processes are closely associated with breccia formation, host rock dissolution, and replacive Fe-Zn-Pb sulfide mineralization due to the ingress of hydrothermal fluids through the fault network.

Traditionally, fluid inclusion geothermometry has been used to study formation temperatures of calcite/dolomite in ore deposits. However, in the Irish orefield fluid inclusions are often stretched, ruptured, or too small for analysis. Consequently, the application of clumped O-C isotope analysis to the Irish orefield has enabled the determination of geologically accurate formation temperatures, facilitating in-depth studies of the evolution of the hydrothermal systems that led to Zn-Pb mineralization. Further, when combined with other isotopic methods (e.g. strontium isotopes), the ultimate origin and subsequent modification of these fluids can be explored. Recent clumped O-C and strontium isotopic studies of limestone, regionally dolomitized limestone, and breccia matrix dolomites from Lisheen and Galmoy have revealed that the fluids involved in early dolomitization and subsequent Zn-Pb mineralization are part of a complex, multistage continuum. This continuum involved fluid-mixing, isotopic resetting and compositional buffering due to carbonate dissolution, ultimately leading to massive sulfide mineralization.
Geology of the Lubambe Cu-Co deposit, Zambia: lithofacies and geochemistry of the Neoproterozoic metasedimentary succession

Aileen Doran, Koen Torremans, Murray Hitzman
Irish Centre for Research in Applied Geosciences (iCRAG), University College Dublin, Belfield, Dublin, Ireland

Jon Stacey
Lubambe Copper Mine Limited, Chililiambwwe, Chingola, Zambia

Deposits in the Central African Copperbelt, the world’s largest and highest-grade sediment-hosted Cu(-Co) district, are hosted by metasedimentary units of the Neoproterozoic Kantangan Supergroup. The full sedimentary sequence from Lower Roan through Nguba to Kundulungu groups is rarely observed in individual drill cores. The Lubambe Copper Mine (previously Konkola North), is a high-grade stratiform Cu-Co deposit (Lubambe Mine: 96 Mt @ 2.1% Total Cu) located at the northern end of the Zambian Copperbelt. Recent deep (1.5 km+) drillholes to the southeast of the Lubambe mine (Lubambe Extension: 247 Mt @ 3.64% Total Cu) penetrated rocks from the Mindola Clastics Formation of the Lower Roan Group up to the Katete Formation in the Nguba Group. Initial lithofacies studies of these drill holes reveal numerous sedimentary cycles with a general evolution from siliciclastic red-bed lithologies upwards to repeating cycles of shales/siltstones-dolostone-evaporite. Deeper water carbonate and siltstones followed this, capped by diamicrites of the Mwale Formation (Grand Conglomérat unit), the basal unit of the Nguba Group. Uniquely in the Lubambe drillholes, there are several thick carbonate intervals between diamicite layers. A combination of multi-element geochemical analysis and pXRF analyses are utilized to geochemically characterize the entire sequence. Consequently, this work will help determine both original depositional units and post-depositional diagenetic and hydrothermal alteration (e.g. potassic, magnesian and sodic). Further, the results of this work will allow for correlation with other regional studies, to further establish facies variation, alteration processes and geochemical trends related to mineralization.

A zircon perspective on the upgrading of heavy mineral sand placer deposits

Maximilian Dröllner, Milo Barham, Christopher L. Kirkland
Timescales of Mineral Systems Group, School of Earth and Planetary Sciences, Curtin University, Perth, Australia

Heavy mineral sands (HMS) are the main source of zircon, monazite and titanium-dioxide minerals and often occur in coastal settings, e.g. as beach placers. A principal control of HMS deposit grade, i.e. the proportion of economic heavy minerals, is the selective removal of labile phases (gangue). Progressive reduction of gangue during abrasion and dissolution processes correlates with the degree of transport, storage and recycling of sediments. However, quantification of these upgrading processes remains challenging. This work aims to determine the degree of sedimentary recycling of HMS via discrimination of first-cycle and multi-cycle detrital zircon (DZ), which represent igneous and sedimentary sources, respectively. We conduct U-Pb geochronology of DZ from (i) modern HMS-bearing coastal sediments in Australia (Scott Coastal Plain) and (ii) deposits in North America. Based on the U-Pb ages, we correlate the DZ to corresponding crystalline basement sources. We then use U and Th concentration to calculate a novel metric – source-normalized α-dose – that is the ratio of the α-dose (a proxy of radiation damage) of DZ grains to the average α-dose value of zircon crystals of corresponding source rocks. We show that this ratio (i) identifies first-cycle sands that are proximal to outcropping crystalline basement and (ii) is sensitive to selective removal of labile DZ during transportation and/or progressive recycling in coastal plain sediments. Furthermore, higher-grade sections of sediments reveal significantly lower source-normalized α-dose than DZ in non-mineralized sections, which captures the enhanced multi-cycle character of HMS. Consequently, results suggest source-normalized α-dose discriminates first-cycle and multi-cycle DZ and, therefore, constrains the degree of multi-cyclicity of HMS. As an exploration tool, this approach may improve constraints of HMS deposit grade and identification of high radioactivity grains that impede profitability.
The origin of pyrite-sphalerite banding in metamorphosed volcanogenic massive sulfide deposits

Brayden Dudley, Stefanie M Brueckner
Department of Earth Sciences, University of Manitoba, Winnipeg, Manitoba, Canada

Volcanogenic massive sulfide (VMS) deposits are commonly metamorphosed to greenschist or amphibolite facies conditions and can exhibit mm to cm thick pyrite-sphalerite banding within the (semi-)massive sulfide lens. The origin of this banding is commonly assumed to be epigenetic as result of metamorphic remobilization and recrystallization. However, similar sulfide banding has been observed in sedimentary exhalative deposits where sulfide banding occurs parallel to bedding. In order to constrain the impact of metamorphism and deformation on the genesis of pyrite-sphalerite banding in metamorphosed VMS deposits, samples from six different metamorphosed VMS deposits (Kidd Creek, Ontario; Flin Flon, Manatoba; Kristineberg, Sweden; LaRonde-Penna, Quebec; Ming, Newfoundland; Mt. Morgan, Tasmania) are investigated using microtexture, microstructure and mineral chemistry.

Textural observations show that pyrite occurs in various textures including: (1) as disseminated, subhedral, recrystallized grains with concave grain boundaries within massive sphalerite (i.e. caries texture); (2) as annealed aggregates of several mm to cm thickness forming triple junctions with neighboring pyrite grains; and (3) as subhedral grains overgrowing a primary, inclusion-rich pyrite core. The microstructure of pyrite in these textures is analyzed using electron-back scattered diffraction and shows varying misorientation angles. Electron microprobe analyses on pyrite and sphalerite show varying trace element content with up to several hundred ppm As and varying Fe content in sphalerite(?) ranging from <5 mol% FeS (Ming) to >10 mol% FeS (Kidd Creek), respectively.

These preliminary microtextural and microstructural results indicate that greenschist to amphibolite facies metamorphism and deformation resulted in the recrystallization of pyrite with internal dislocations at various angles in all studied deposits. In contrast, chemical composition of both pyrite and sphalerite is highly variable among the studied VMS deposits, albeit independent of texture and hence indicates that chemical composition is rather a function of syngenetic fluid conditions than the result of epigenetic metamorphism and deformation.
Spatial controls, mineralogical variation and paragenetic sequence of the mineralization and alteration at the Rosh Pinah Zn-Pb deposit, Namibia

Halleluya Naantu Ekandjo, John F. Güven, Koen Torremans, Murray Hitzman, Sean Johnson*
Irish Centre of Research in Applied Geoscience (iCRAG), School of Earth Sciences, University College Dublin, Ireland
* now at Boliden A.B., Boliden Mines, Sweden

Linus Flavianu, Katrina Kantene, Sheron Kaviua, Yan Bourassa
Trevali Rosh Pinah Zinc Corporation, Rosh Pinah, Namibia

The Rosh Pinah Zn-Pb-Ag (Ba) deposit is located approximately 22 km north of the Orange River in the southernmost part of the Namib Desert and has been in production for over 52 years. It is hosted by the volcano-sedimentary units of the Rosh Pinah Formation (Hilda Subgroup of the Port Nolloth Group) which forms part of the Neoproterozoic Gariep Terrane. The rocks experienced greenschist to lower amphibolite facies metamorphism. The deposit comprises a significant sulfide resource (18.13 Mt @ 7.5% Zn, 1.87% Pb and 27.7 g/t Ag). Its metallogenesis remains unclear, although it has been proposed to represent a sedimentary-exhalative type deposit, and volcanic origins or contributions have also been suggested. Significant felsic volcanic and volcaniclastic rocks, along with minor mafic volcanic flows, are present in the Rosh Pinah basin near the deposit, including near the westernmost orebody and Eastern Orebody.

This study will present the paragenetic sequence of mineralization, alteration and deformation and the 3D distribution of these aspects of the deposit. It combines whole-mine scale 3D subsurface data and modeling with detailed petrography, pXRF, whole-rock geochemical data and laser ablation ICP-MS data. Distinct mappable facies zones are present at the stratigraphic level of the orebody that correlate with the style of mineralization, while work on metal zonation points to possible multiple feeders within the deposit which display increased copper contents. Observations from drill core show limited alteration halos proximal to mineralization. The footwall to mineralization is often intensely silicified and brecciated with disseminated and stringer sulfides filling fractures. Preliminary petrography work indicates that original sedimentary and diagenetic textures are surprisingly present in some of the carbonates. Further work on the carbonates may yield important clues as to the depositional environment. Reflected light microscopy has demonstrated a mineralogically simple sulfide suite showing complex intergrowths with barite.
Geochemistry of antimony mineralizations in La Balanzona and Accesos mines, Central Iberian Zone, Spain

José-María Esbrí
Departamento de Geología y Geoquímica, Universidad Complutense de Madrid, Spain
Instituto de Geología Aplicada, Universidad de Castilla-La Mancha, Spain

Carmelo Minang, Saturnino Lorenzo, Sofía Rivera, Jesús Peco,
Mercedes Madrid, Eva García-Noguero, Pablo Higueras
Instituto de Geología Aplicada, Universidad de Castilla-La Mancha, Spain

Maite Maguregui
Departamento de Química Analítica, Universidad del País Vasco, Spain

Ana González Valoys
Instituto de Geología Aplicada, Universidad de Castilla-La Mancha, Spain
IES Mercurio (Almadén), Spain; Universidad Tecnológica de Panamá, Panama

Antimony (Sb) mineralizations often exhibit a paragenesis dominated by stibnite (Sb$_2$S$_3$) and their oxidized phases. Knowing in detail the mobility parameters of Sb in this type of mineralization is of crucial importance for geochemical prospecting of this type of deposits, as well as for managing their mining in an environmentally sustainable way. The present work uses the abandoned mines of Accesos (Ciudad Real) and La Balanzona (Córdoba) to carry out an evaluation of these aspects.

Two types of sampling have been carried out in the areas of interest: one of soils and mining materials, focused on obtaining chemical and mineralogical data from these two mines; and a second one sampling soils in a regular grid in the La Balanzona mine, focused on obtaining data on the mobility and dispersion of the element as a result of mining.

The main sulfide phases found were stibnite (Sb$_2$S$_3$) in Accesos and La Balanzona, and tetrahedrite ((Cu,Fe)$_{12}$Sb$_4$S$_{13}$) in Accesos mine, whereas the main oxidized phases were bindheimite (Pb$_2$Sb$_2$O$_6$O) and stenhuggarite (CaFe(AsO$_2$)(AsSbO$_5$)) in two of the mines; and senarmontite (Sb$_2$O$_3$) and valentinite (Sb$_2$O$_3$) in the Accesos mine.

Although total Sb reaches extremely high concentrations in the La Balanzona soil survey (3,069 mg kg$^{-1}$), the dispersion area of Sb around the mine appears restricted to 150 m (<400 mg kg$^{-1}$) or 400 m (<100 mg kg$^{-1}$). A BCR sequential extraction has shown 99.5% of Sb in the residual fraction, with extremely low values of Sb bound to organic matter or to Fe oxyhydroxides in a few samples. Enzymatic activities show levels around 100 µg TPF d$^{-1}$ g$^{-1}$ of DHA, that seems to be not affected by the presence of the Sb compounds in the soils. In conclusion, Sb has shown very low mobility and a negligible effect on the soil health.
Application of a geochemical-mineralogical approach to sulfidic tailings from Neves Corvo mine, as an indicator for future mining and remediation

Alexandra Gomez Escobar, Jorge M.R.S. Relvas, Álvaro M.M. Pinto
Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

Mafalda Oliveira
SOMINCOR-Lundin Mining, Neves Corvo Mine, Castro Verde, Portugal

About 90% of the tailings produced at Neves Corvo mine, since the late 80’s, are heavy metal-bearing sulfides, which required a very specific disposal system, that can be environmentally safe but keeping open the possibility of future mining and the recovery of residual values in Cu, Zn, Sn and other by-products (such as In, Se, Co, Ag and Pb), and guaranteeing the geochemical stability of sulfides to prevent oxidation of pyrite and other potential acid rock drainage (ARD) generators.

This study addresses the characterization of tailings stored at the Cerro do Lobo TSF in Neves Corvo mine, a world-class underground Cu-(Sn)-Zn-Pb operation located in the Iberian Pyrite Belt (Portugal). The nature and management of the case study focuses on a CPTu campaign and representative sampling for assessment of soil parameters and behavior of tailings. The combination of geochemical parameters (pH, conductivity, salinity, moisture, chemical-metal content) with geotechnical indicators (local friction, pore shoulder and tip resistance) and automated quantitative mineralogical analysis (MLA, EPMA) is aimed to provide predictive indicators of potential for future mining with subsequent resource estimation, and perfect criteria for comparison with ARD tests such as Net Acid Generation (NAG) and Acid Base Accounting (ABA).

Preliminary results from geochemical parameters suggest that moisture at Cerro do Lobo TMF varies from 17-34%, with the higher values found in samples closer to the surface where water is constantly being removed. In general, tailings showed values of pH around 7-9, indicating basic and homogeneous conditions for the tailings from bottom to surface. D$_{80}$ values present higher variability (range from 17 to 150 µm) considering the disposal method and the pastefill/backfill operations. Soil Behavior Type (SBT) classification implies the material are clays to sandy clays which complies with the D$_{80}$ results obtained. Semi-quantitative XRD analysis confirms pyrite and quartz as the main constituents of Neves Corvo tailings, with 46.6 wt% and 24.4 wt%, respectively.
Trace element deportment – knowledge is power

Angela Escolme  
Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Hobart, Tasmania, Australia

Over the past century, mankind’s appetite for metallic resources from mineral deposits has grown dramatically, in step with technology and population growth. Under the foreboding clouds of a changing global climate, governments across the globe have pledged to reduce CO₂ emissions and transition toward a carbon-neutral future. The road to this carbon-neutral world will be paved by metals that still need to be extracted from mineral deposits, which are largely yet to be found or developed. The demand for metals like Cu and Co in low emissions electricity generation and storage must also drive innovation in the minerals industry to increase not just discovery, but also recovery. Many critical metals occur as trace elements in ore deposits for other major commodities (for example Co is a by-product from sedimentary-hosted Cu and massive Ni-sulfide mines), but in many cases these trace elements are not typically recovered (for example REE’s in IOCG deposits) for a variety of reasons which may include lack of an obvious production flow-sheet. Characterizing the occurrence of critical metals early in project studies facilitates recovery options for these commodities to be considered during metallurgical circuit design. Just as society had embraced recycling, and now many consider it abhorrent to put aluminium cans or glass into landfill, so the minerals industry and its stakeholders should object to critical metals languishing in tailings dams or waste dumps. Waste materials of the past are now considered deposits of the future with reprocessing becoming increasingly feasible for many sites. Never before has it been so important to break down silos and have geologists and metallurgists work together to solve a global critical metal supply issue and increase the range of metals recovered from ore deposits. A robust approach to geological characterization that reveals discrete populations of mineralogy, texture and trace element deportment is the cornerstone of future recovery opportunities.

Mineralizing fluids in the Catalina Huanca carbonate-replacement Zn-Pb-Ag deposit, southern Peru

Iván Mateo Espinel Pachón¹, Antoine de Haller¹, Kalin Kouzmanov¹, Peter Tollan², Jorge E. Spangenberg ³  
¹ Department of Earth Sciences, University of Geneva, Geneva, Switzerland  
² Institute of Geochemistry and Petrology, ETH Zürich, Zürich, Switzerland  
³ Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland

Catalina Huanca is a carbonate-replacement Zn-Pb-Ag deposit in the Andean Cordillera of southern Peru. The mineralization consists of veins and replacement bodies.

A detailed microthermometric and LA-ICP-MS study on fluid inclusions in fluorite, quartz and sphalerite was performed for the early and late polymetallic stages in five ore bodies. Microthermometry of the nearly opaque early-stage sphalerite was performed using near infrared microscopy. All studied primary fluid inclusions are two-phase (L+V), with homogenization temperatures between 220° and 350°C, and salinities ranging from 2 to 16 wt% NaCl equiv.

The sulfur isotope ratios (δ³⁴S in ‰ vs VCDT, n = 26) in early pyrite and sphalerite, and late chalcopyrite and sphalerite range between 7.0 and 8.5 ‰ while those in late pyrite and galena between 4.8 and 6.5 ‰. These values suggest a magmatic source for reduced sulfur (around 8 ‰) higher than usual. The variations of δ³⁴S values can be explained by different S isotope fractionations associated with changes in temperature and concentrations of S phases of different oxidation states.

The element ratios and concentrations of Cl, Br, Na, K and Rb in FIs are indicative of a magmatic origin of the fluids. Element concentrations plotted versus Cl show two trends: i) constant elemental concentration, which is associated with the early high-temperature polymetallic stage in Mariela and probably corresponds to a boiled, acidic, metal-rich, magmatic fluid that interacted with carbonate rocks; and ii) a progressive decrease of fluid salinity and temperature during the precipitation of early and late polymetallic stages in Amanda 3 Techo, Melissa and Principal. The concomitant shift towards higher B/Cl suggests important dilution of the early fluid by low-salinity magmatic-vapor condensate. The FI compositions and the paragenetic sequence are consistent with pH buffering by the host carbonate rocks and temperature decrease as the main parameters controlling ore precipitation.
An improved generative adversarial network for mapping geochemical anomalies

Ehsan Farahbakhsh¹, Behnam Sadeghi¹,², R. Dietmar Müller¹, Rohitash Chandra³ ⁴
¹EarthByte Group, School of Geosciences, University of Sydney, NSW, Australia
²School of Biological, Earth and Environmental Sciences, University of New South Wales, NSW, Australia
³School of Mathematics and Statistics, University of New South Wales, NSW, Australia
⁴UNSW Data Science Hub, University of New South Wales, NSW, Australia

Geochemical data are among the critical data types used at different stages of mineral exploration to identify ore deposits and mineralization processes. Mapping geochemical anomalies related to target mineralization and integrating them with other data types are essential for determining potentially mineralized zones. In the past decades, a variety of analytical methods have been developed for geochemical data processing, and different problems associated with them have been addressed. Recently, machine learning methods have been of interest to the community of exploration geologists and applied for processing geochemical data and predicting anomaly zones. Among different categories of machine learning methods, deep learning can be used to deal with complex and non-linear geochemical data and enhance geologists’ ability to recognize hidden patterns. This study used an improved generative adversarial network (GAN) to detect mineralization-related multi-variate anomalies of a class imbalance geochemical dataset. Class imbalance in a geochemical dataset is a significant problem for classifiers and results in poor prediction of mineralized zones. Our proposed method improves the accuracy of potential maps by combining the advantages of GAN and the synthetic minority over-sampling technique (SMOTE) and overcomes the class imbalance problem. We performed various experiments to construct an efficient network to process multi-dimensional geochemical data and identify geochemical anomalies associated with copper mineralization in a region located within the Macquarie Arc terrane, New South Wales. Based on the results, this method is able to identify internal connections and characteristics between multi-variate geochemical data and avoid the noise influence in predictions. The extracted anomaly zones show a strong spatial relationship with known mineral occurrences and demonstrate that deep learning methods can efficiently delineate potentially mineralized zones in geologically complex areas.
Lithospheric architecture of the central Andes and the localization of giant porphyry copper deposits during key geodynamic epochs

Alexander Farrar, David R. Cooke, Matthew Cracknell
Centre for Ore Deposits and Earth Sciences (CODES), University of Tasmania, Hobart, Australia

Jon Hronsky
Western Mining Services, Perth, Australia; and CET, University of Western Australia, Perth, Australia

José Piquer
Universidad Austral de Chile, Valdivia, Chile

The central Andes is the most important copper province on the planet, producing over 40% of the world’s annual output. Giant porphyry copper deposits in the central Andes cluster in discrete geographic camps of a similar age, indicating that exceptional transient geologic processes affected localized regions of the lithosphere around the age of mineralization. The development of favorable regions of lithosphere for significant metal concentration are thought to be linked to the overlap of structural pathways that focus fluid and magma flow from the mantle to upper crust. This research employs a multi-scale and multi-disciplinary approach to understand the nature of the structural architecture thought to control the focused vertical ascent of fluids and magma through the lithosphere.

Field mapping undertaken at multiple scales throughout the central Andes demonstrates that on the surface a translithospheric fault is expressed as linear zones of brittle faulting, 10–25 kilometers wide and hundreds of kilometers long. This is interpreted to reflect the upper crustal propagation of the underlying zone of basement weakness through younger sequences in the geologically active convergent plate margin. We postulate that the translithospheric fault architecture of the central Andes formed in response to the interplay of the orientation of accreted terrane suture zones, inherited structural weaknesses and the orientation of Paleozoic and Mesozoic extensional events. During compression and lithospheric thickening, these steep zones of lithospheric permeability were reactivated during periods of high lithospheric coupling, which provided a permeability pathway from the upper mantle to the upper crust, through the lower crust during high strain events. A compelling relationship is observed between the locations of known giant porphyry deposit camps and where two or more translithospheric faults intersect. Such regions are inferred to have been zones of deep dilation, triggered during transient events that affected the stress field.
Closing mines, greening economic trajectories, and building territorial capability - the triad of a sustainable post-mining territory: the systemic ecological transition of Loos-en-Gohelle, France

Daniel Florentin, Thomas Beaussier, Margaux Blache, Cécile Schwartz, Marie Veys
Mines Paris Tech, Institut Supérieur d’Ingénierie et de Gestion de l’Environnement (ISIGE)

As surprising as it may seem, one of the epigons of ecological transition in France is a small former mining city, Loos-en-Gohelle (population 7,000), where mining activities ceased in 1986. Mining left the highest density of mining pits in one single city Europe-wide, yet in 2011 the city was branded a national pilot for urban sustainable development. The area has concentrated a lot of public and academic attention ever since. How did such rejuvenation occur and what can this be the model of? Loos-en-Gohelle’s trajectory is often reduced to a sole transition from black to green through the development of new activities epitomizing the green and low carbon economy. Yet, this remains fairly simplistic and neglects both the intense labor of valuation of former activities led by the local authority and the systemic, highly reflexive, and collective practice that was developed by the authorities and their population. Using the theoretical framework of territorial capability, this paper shows how the transition of this former mining hotspot rests on the complex convergence of three processes: the valuation of the inheritance of mining activities in a non-folkloric nor dated way (through cultural events and the mobilization of the local population); the political creation and animation of an economic hub around low carbon urban production; and the articulation of different scales to anchor this local project in larger visions of systemic territorial transformations (and notably around the Third Industrial Revolution that irrigates the regional development policy). Based on fieldwork visits and 20 interviews with key local representatives, it anchors the production of territorial capability in the enactment, activation and (re)production of territorial resources, be they material, political or symbolic.
Global Production Networks and the lithium industry: a Bolivian perspective

Marie Forget  
Savoie Mont Blanc University, EDYTEM UMR 5204, France

Bos Vincent  
Loraine University, Georessources UMR 7359, France

This presentation provides the first detailed analysis within economic geography of the Global Production Network (GPN) of lithium and of the Bolivian strategy of brine industrialization. Considering extractive and manufacturing chains of the lithium industry, it demonstrates how the production networks’ organizational structures and practices are shaped by interconnected relations of cooperation and competition. The characterization of the GPN allows a richer understanding of the global economy of lithium by breaking down its different stages and isolating key players and territories in a global context of growing interest for lithium, mostly from extractive and industrialized stakeholders who wish to ensure their access to the resource for their production of lithium-ion batteries for the electronics and the automotive sectors. The so-called “lithium triangle” constitutes a global node of the GPN. The ongoing restructuring and verticalization of the GPN contributes to the reinforcement of the region in the global geopolitics of lithium. Pioneers stakeholders have increased their presence while the extractive chain is challenged by newcomers from both the Global North and the Global South. Bolivia shows a specific profile as a resource-holder state trying to develop both public extraction and industrialization.

Specifically, this presentation targets two key points in the GPN literature: i) how the multi-scalar competitive and/or cooperative strategies and practices of forward and backward integrations create and sustain the production networks and their evolution; and ii) a combined analysis of the GPN approach with a placed-based interpretation of the political economy of the lithium industry focusing on the central role of states as inter-scalar mediators in strategic coupling relations for the insertion of national economic actors and assets to global markets. We then propose a new interpretation of the global reconfiguration of the extractive chain and its spatial forms.

Building transition resources: geo-legal approaches to lithium brines in the salt flats of South America

Marie Forget  
Savoie Mont Blanc University, EDYTEM UMR 5204, 5 Bd de la Mer Caspienne, Le Bourget-du-Lac, France

Bos Vincent  
Loraine University, Georessources UMR 7359, 92, rue du Sergent Blandan, Nancy Cedex, France

Chloé Nicolas-Artero  
Center for Climate and Resilience Research, Chile

The exploitation of Andean lithium questions the production of space through brines, their circulations between subsoils and surface, and its repercussions on the daily sharing of water between mining and agricultural users. The soils and subsoils of salt flats are thus considered as material layers configured by an interweaving of actors, divergent interests and socio-technical systems. This presentation analyzes the rise of lithium exploitation through geo-legal strategies of re/de/construction of the resources “lithium” and “water” aiming to favor or restrict the appropriation of space according to the actors considered. It demonstrates that the control of the resource and the productive organization of the lithium space can be explained by (1) the development of geo-legal strategies by the State and mining companies, (2) the construction of lithium resources based on a legal construction differentiating the brine from fresh water, and (3) the development of geo-legal tactics by local populations with the objective of reappropriating the local territory.

Studying lithium exploitation in Chile from a geo-legal perspective thus extends reflections on the relationship between the geography of natural resources and environmental law and offers elements for discussion on the legal construction of nature. The diachronic and multi-scalar approach mobilized allows us to denaturalize the mining and water legal regimes in Chile. These regimes are not neutral and have effects on the production of extractivist spaces.
Nanoscale heterogeneous distribution of Ge in plastically deformed sphalerite

Denis Fougerouse, Steven M. Reddy
School of Earth and Planetary Sciences, and Geoscience Atom Probe Facility, John de Laeter Centre, Curtin University, Australia
Alexandre Cugerone
Géosciences Montpellier, University of Montpellier, France
University of Geneva, Department of Earth Sciences, Switzerland

The demand for critical metals is growing due to their importance in a range of key industrial and consumer devices such as personal electronics, photovoltaics and optical fibers. Germanium can be found as a by-product of base metal mineralization (Pb-Zn-Cu) and is commonly hosted in sphalerite [ZnS]. Previous work suggests that Ge, Ga and Cu are incorporated in the sphalerite lattice by solid solution and can be remobilized during deformation-related recrystallization of sphalerite. However, the nanoscale processes responsible for the redistribution of trace elements during crystal-plastic deformation of sphalerite and/or fluid-rock interaction remain poorly constrained. In this contribution, we investigate naturally deformed Ge-rich sphalerite from the Mesozoic epigenetic vein-type deposits of the Western French Pyrenees by using a combination of electron backscattered diffraction (EBSD), laser-induced breakdown spectroscopy (LIBS) and atom probe tomography (APT). Our results show that the sphalerite studied is a polycrystalline aggregate with evidence of dynamic recrystallization during deformation. At the nanoscale and in undeformed crystal domains, Ge is dominantly associated with Cu and Fe in the form of primary briarite [Cu₂FeZnGeS₄] nano-inclusions (diameter ~5 to 50 nm) rather than in solid solution. Deformation microstructures such as low-angle and twin boundaries were found to be enriched with trace elements such as Cd but not Ge, indicating that deformation microstructures did not collect Ge during boundary migration or alternatively acted as a fast diffusion pathway for Ge remobilization.

Soil sampling campaign and geochemical analysis in the Ribeiro da Serra Mine (Gondomar, Portugal)

Rui Frutuoso, Alexandre Lima, Filipe Soares, Ana Carvalho, Maria Ribeiro
Institute of Earth Sciences, FCUP Pole, Porto, Portugal

A regular soil sampling campaign was carried out in the historic Ribeiro da Serra Mine (Sb-Au), located in the western limb of the Valongo Anticline (Portugal). This antimony deposit is one of the main deposits exploited in late 19th century. In total, 157 shallow-soil samples (B and C horizon) have been collected and were chemically analyzed with a portable X-Ray Fluorescence (pXRF) analyzer. Although the studied area was strongly affected by human activities, by the old mining workings and by the intense eucalyptus plantation, it is possible to consider the results of this campaign trustworthy. Through a Pearson correlation matrix, it was observed that Mn has a very strong correlation with Zn and a strong correlation with Pb. Consequently, a strong correlation between Pb-Zn occurs. Antimony appears weakly correlated with Pb, while a strong inverse correlation is observed for Ti-As. Antimony anomalies can be observed on the surface of underground workings, as well as on the vein occurrences within the Schist-Greywacke Complex (SGC). An elongate downstream anomaly is present and may be related to contamination and sediment transport. At the NW edge of the sampling grid a high concentration anomaly is observed, possibly due to the presence of a fault related to the Fontinha Mine, which may have acted as a mineralization conduit. Arsenic anomalies are especially present around quartz veins located near the contact between lithologies. A strong anomaly is present in the NW region, and is possibly related to quartzite intercalations in SGC. Manganese, zinc and lead anomalies are similarly related in the southern region, where the mining facilities were located, which may indicate that these are associated with the contamination from mining activity. Multielement pXRF analyses enabled identification of associated pathfinder elements and confirmed the effectiveness of this tool in locating the occurrence Sb-rich veins.
Listwanite-hosted epithermal gold mineralization in an island arc: insights from the Malabeg prospect, Cabangan, Zambales, Philippines

John Emmanuel S. Fungo1, Jillian Aira Gabo-Ratio1, Kotaru Yonezu2, Karl D. Jabagat3, Marco Alfredo J. Barrientos1 and Kyoichi Ito4

1National Institute of Geological Sciences, University of the Philippines, Diliman, Quezon City, Philippines
2Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka, Japan
3Department of Earth and Environmental Sciences, National Chung Cheng University, Taiwan, R.O.C.
4Exploration Department, Mineral Resources Division, Sumitomo Metal Mining Co. Ltd, Tokyo, Japan

The Malabeg prospect is a listwanite-hosted epithermal deposit in the Zambales Ophiolite Complex, northern Luzon, Philippines. Mineralization is associated with NW-trending quartz veins found along contacts of peridotite and diabase and in open spaces within the host rocks.

Four stages of alteration and vein development are identified. Stage 1 is represented by talc-carbonate alteration of the peridotites. Stage 2 is represented by dolomite veins cutting the host rocks. Stage 3 consists of quartz-calcite veins with arsenopyrite. Stage 4 quartz-adularia veins are represented by chalcopyrite, pyrrhotite, pyrite à galena, sphalerite à electrum. Electron microprobe analysis of electrum revealed a mean value of 74.33% Au and 21.55% Ag. The mean iron-sulfide mole percent value for sphalerite is 14.91% from nine sphalerite points coexisting with pyrrhotite or pyrite. Based on these values complemented by the sulfide assemblage, the Malabeg prospect has an intermediate sulfidation state.

Two distinct hydrothermal processes were recognized for the Malabeg prospect. Stages 1-3 represent the initial pulse of intermediate sulfidation fluids related to magmatic activity within the Bataan Volcanic Arc. This caused the listwanitization of the host rocks. The altered zone became susceptible to brittle deformation processes such as faulting, producing open spaces such as fractures. Stage 4 quartz-adularia veins are precipitated into these open spaces by subsequent fluids. The relatively lower sulfur activity is attributed to the strong rock buffering capacity of the ferromagnesian minerals from the peridotites. It also coincides with the ‘auriferous vein’ classification which has lower sulfur activity compared to electrum with higher silver and are usually hosted in regionally metamorphosed units.
Several aspects of the massive concentration, origin and evolution of sulfides in the mineralized Norilsk-type intrusions still remain unknown. Geochemical and petrographic evidence on disseminated sulfide ores, platinum group minerals (PGMs) and their corresponding magmatic host-rocks is presented in order to provide new insights on the evolution of the ore system and its relation to the emplacement and crystallization from one or more magma pulses. Using samples from the main ore horizon (MOH) of core sample PH-265, located in the middle part of the Norilsk 1 intrusion and by means of SEM-EDS and ICP-AES, it was established that the MOH consists of at least three different rock types of apparent cumulative origin, that according to their modal composition, texture and typomorphic minerals correspond to: picritic gabbro-dolerite (g-d), taxitic texture g-d and olivine-bearing g-d. The following two main sulfide paragenesis are interpreted: Low-S association Tro + Pn(Fe) + Ccp + Cub in picritic rocks and High-S association in taxitic and olivine-bearing g-d consisting of Po(mo-hex) + Pn(Ni) + Ccp ± Sph, with whole rock Ni/Cu ratio <1 for the former and >1 for picritic g-d. In addition, these ores exhibit similar composition in 100% sulfide patterns and a compositional evolution trend of base metal sulfides which evidences a gradual thermal gradient that decreases to the base of the sill, as well as an increase in f(S2) in the same direction. At first glance, the revealed characteristics in ores suggest a possible evolution from two different sulfide melts, associated to two different pulses of magma. However, different studies have demonstrated their isotopic affinity, therefore marginal in situ modification through assimilation of country rock combined with the presence of a compositional boundary layer imposed by a thermal gradient in a sulfide liquid of identical composition is here discussed and must be further investigated.
Exploration history of the Wharekirauponga low-sulfidation epithermal Au-Ag deposit, Hauraki Goldfield, Coromandel, New Zealand

Thomas Gardner, Lorrance Torckler
OceanaGold, Waihi, New Zealand

At Wharekirauponga, exploration in the last five years has discovered an estimated indicated resource of 1.0 million tonnes @ 13.4 g/t Au (421,000 ounces Au). Gold was first discovered at Wharekirauponga in 1888 in narrow quartz veins in rhyolite outcropping in a gorge along the Wharekirauponga Stream. A mine was developed, consisting of a series of underground workings and on-site infrastructure, but the prospect was abandoned by 1898 due to uneconomic gold grades.

Modern exploration of the prospect began in 1978 with the first drill hole commencing in 1980. Over the next decade, three companies completed 23 diamond drill holes for approximately 5500 m at Wharekirauponga with most of the exploration centered around the exposed quartz veins. Drilling showed the potential for a large, well-mineralized, low grade epithermal Au-Ag system.

Skipping ahead two decades to 2010, exploration at the prospect was renewed under Newmont and joint venture partner Glass Earth. The exploration strategy differed to that of prior explorers, with the focus shifting to the discovery and testing of larger, prospect scale structures with the potential to be mined from underground. Through detailed surface mapping of the prospect and utilization of geophysics - primarily CSAMT resistivity, key structural zones were interpreted and tested over the next three years through the drilling of 17 drill holes for approximately 9000 m. This drilling led to the definition of three significant vein zones – the T-stream vein, East Graben vein and the Western vein zone.

In 2015, OceanaGold acquired Newmont’s New Zealand assets, including the Waihi Gold Mine and their exploration tenements in the district. OceanaGold commenced drilling at Wharekirauponga in 2017, with the primary focus being to follow up the previous drilling on the East Graben vein. OceanaGold’s first and third drill holes confirmed a significant discovery was in the making.
Developing trace elements in pyrite as a petrogenetic discriminant tool for gold mineralization: example from the Abitibi greenstone belt, Canada

Dominique Genna
CONSOREM-UQAC, Université du Québec à Chicoutimi, Unité des Sciences de la Terre, Chicoutimi, QC, Canada

Damien Gaboury, Sarah Dare
UQAC, Université du Québec à Chicoutimi, DSA, Unité des Sciences de la Terre, Chicoutimi, QC, Canada

Christophe Azevedo, Michel Jébrak
UQAM, Université du Québec à Montréal, Département des Sciences de la Terre et de l’Atmosphère, Montréal, QC, Canada

A wide typology of gold mineralization has been described in the Abitibi greenstone belt ranging from synvolcanic to syntectonic deposits. Most syntectonic deposits are interpreted as orogenic and formed by metamorphic fluids. A magmatic-hydrothermal contribution, although well recognized and accepted in the synvolcanic type, remains highly debated in syntectonic deposits. Independent of the mineralization style, most syntectonic gold deposits are located along major structures (e.g. Cadillac fault, Abitibi) and hosted in deformed and metamorphosed terranes, thus making the identification of a possible magmatic-hydrothermal fluid contribution difficult. Early detection of a magmatic input would have a significant impact on exploration strategies used for future gold deposit discoveries. In this study we have investigated the trace element signature of more than 1000 pyrite grains, using LA-ICP-MS, from 19 syntectonic deposits located in the Abitibi greenstone belt. Our case studies are representative of: 1) classic Archean orogenic vein-type mineralization, hosted in intrusions (e.g. Goldex) or volcanic rocks (e.g. Perron); 2) arsenopyrite-rich disseminated sediment-hosted deposits (e.g. Vezza); and 3) intrusion-associated deposits within intermediate (e.g. Douay) or spatially associated to felsic intrusions (e.g. Bachelor) of alkaline affinity and where a hydrothermal-magmatic contribution is suspected but debated. We propose a new multielement discrimination diagram, normalized to Archean sedimentary pyrite, showing that the variability of the dataset is best explained by 1) the source of the fluids and 2) the conditions of precipitation. Specifically, pyrite from the orogenic vein-type is depleted in most trace elements. Only the Au-Co-Ni content is similar to sedimentary pyrites. Pyrite from sediment-hosted deposits is enriched in Au-As-Sb-W. Disseminated pyrite associated with alkaline intrusions are characterized by an overall higher abundance of most trace elements with positive Au-Se-Te-Ag-W-Tl anomalies. Such a signature is almost identical to modern alkaline porphyry deposits where the magmatic contribution of gold and fluids has been demonstrated.
Magma fertility in Brothers submarine volcano

Ariadni Georgatou, Cornel E.J. de Ronde
GNS Science, Lower Hutt, New Zealand

Submarine arc hydrothermal systems are considered to be modern analogues of fossilised volcanic-hosted-massive-sulfide deposits (VHMS) on land and also present similarities to shallow parts of porphyry-Cu and epithermal-Au deposits also occurring on land. Although there are numerous studies investigating the potential of a magma to form an economic deposit, known as “magma fertility”, on arc magmas in subaerial systems, there is limited related information on submarine systems. The Brothers active submarine volcano, situated along the Kermadec arc, is one of the most well-studied systems and actively forming Cu-Zn-Au-rich black smoker chimneys (Cu$_{max}$ = 36 wt.%). Recent studies suggested that Brothers represents a high sulfidation deposit on the seafloor with evidence for a magmatic input possibly due to an underlying porphyry-Cu deposit providing a fertile source for metals and magmatic volatiles.

Here we investigate the source and transport of Cu and Au as well as the magma efficiency to concentrate these metals in order to produce the known VHMS deposit at Brothers. Bulk metal contents from newly acquired fresh dacitic samples collected from the caldera wall by an ROV yield ranges for Cu = 1.4-40 ppm and Au = 0.6-1.5 ppb, comparable to other known porphyry-related magmatic systems. Meanwhile, magmatic sulfides ≤500 μm, found in the lavas and in unusually sulfide-rich enclaves (~20 area%), are composed of mainly pyrrhotite and chalcopyrite (Cu<24 wt.%) and often show sulfide-oxide replacement textures. Preliminary results suggest that although sulfides have sequestrated metals in depth, rendering the residual magma Cu-Au-poor, sulfide dissolution in shallower levels, lead to metal release back to the system causing a later metal enrichment of the exsolving fluids. Future LA-ICP-MS on melt inclusions will help constrain better the initial Cu and Au contents of the system.

Ore-forming conditions at the Gorno MVT district, Lombardy, Italy

Michele Giorno¹, Carlo Bertok¹, Luca Martire¹, Luca Barale², Mathias Burisch³ ⁴, Max Frenzel⁴, Nathan Looser⁵, Stefano M. Bernasconi⁵
¹Department of Earth Sciences, Univerità degli Studi di Torino, Italy
²CNR IGG – Torino, Italy
³Technische Universität Bergakademie Freiberg, Germany
⁴Helmholtz-Zentrum Dresden-Rossendorf, Germany
⁵Department of Earth Sciences, ETH Zürich, Switzerland

The stratabound, carbonate-hosted Pb-Zn-Ag (± fluorite ± barite) deposits of the Gorno mining district extend over ~600 km² in the Orobic Alps, Lombardy, Northern Italy. The district has classically been described as an “Alpine-type” Pb-Zn deposit, a subclass of Mississippi Valley Type (MVT) deposits. Its genesis is still debated. Multiple events affected the Lower Carnian stratigraphic succession, resulting in variable styles of host rock alteration and sulfide mineralization. High-grade sulfide ore is hosted in the 5-10 m thick basal unit of the Gorno Formation, consisting of a laminated marl and siltstone lithozone, historically known as “black shales”. Other major orebodies are hosted in the 50-100 m thick Breno Formation, composed of light-coloured, thick-beded peritidal limestones and in the 20-50 m thick Calcare Metallifero Bergamasco, composed of dark-coloured, medium-beded peritidal limestones.

In situ U-Pb isotope analyses were performed on sulfide-associated carbonates, revealing an average lower intercept age of 229.2 ± 2.9 Ma, i.e. slightly younger than the depositional age of the host rock (~237-232 Ma). This represents the first geochronological data for the district, indicating mineral deposition during early diagenesis at relatively shallow burial depth. Microthermometric data from sphalerite and fluorite suggests an evolution from high salinities (up to ~25 eq. wt% NaCl) towards lower salinities (typically <10 eq. wt% NaCl). The homogenization temperatures do not vary significantly, ranging between ~80 and 120 °C and do not show a correlation with salinity. Additionally, micro-Raman spectroscopy revealed the presence of methane in primary fluid inclusions.

The spatial association of sulfide bodies to organic-rich shales supports a lithological control of ore deposition. Clay-rich beds with organic carbon or associated hydrocarbons are hence proposed to have acted as reactive barriers that caused reduction of the metal-bearing hydrothermal fluids migrating along fault and fracture systems.
Portuguese Variscan granites with metallogenic potential: what are their geological, petrophysical and geochemical signatures?

Ana Gonçalves, Helena Sant’Ovaia, Fernando Noronha

Universidade do Porto, Faculdade de Ciências, Departamento de Geociências, Ambiente e Ordenamento de Território, Instituto de Ciências da Terra, Polo Porto, Porto, Portugal

Increasing demand for Critical Raw Materials (CRMs) requires the development of innovative indirect and non-invasive tools in the exploration for new CRM ore deposits. Our study involved the recognition of signatures indicative of Sn-W prospectivity of granites in the "Sn-W Iberian Metallogenic Province" of Portugal where the Sn and W deposits exhibit a strong association with Variscan granites. Six S-type peraluminous granite plutons (Capinha, Numão, Arnozelo, Cachão de Arnozelo, Custóias and Freixo de Numão) intruding similar Lower Cambrian-Upper Precambrian metasedimentary sequences were investigated. The Capinha pluton, located in Fundão (Central Portugal), occurs in the contact between the metasediments and older granites, and the other plutons, situated in Vila Nova de Foz Côa (Northern Portugal) intruding metasediments. Therefore, a multidisciplinary approach (fieldwork, mineralogy, petrophysics - magnetic susceptibility and geochemical studies) was applied. These methodologies enabled the identification of features characterizing the metallogenic potential of the granites, namely: (i) the granites must be hosted in metasediments or near the contact between metasediments and older granites; (ii) the granites must be muscovite-rich (muscovite I > biotite); (iii) the emplacement of granite magmas must have been conditioned by extensive NNE-SSW to NE-SW faults; (iv) the magnetic susceptibility must be low (< 70 µSI); and (v) the granites must display strongly differentiated patterns characterized by low K/Rb (~ 83), low ΣREE (11.76-79.34 ppm) and low negative Eu anomalies (0.13). In short, the granites that gather these features are Custóias (31 ppm Sn, 6.6 ppm W), Arnozelo (55 ppm Sn, 11-16 ppm W) and Capinha (9-24 ppm Sn, 6-12 ppm W).
Application of chlorite geothermometry to the Hishikari gold mine, Japan: implication for the upflow zone in the low-sulfidation epithermal system

Yuji Gono1, Akira Imai1, Kotaro Yonezu1, Thomas Tindell1, Adrian J. Boyce2, Jun-ichiro Ishibashi3

1 Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka, Japan
2 Scottish Universities Environmental Research Centre, Scottish Enterprise Technology Park, East Kilbride, Glasgow, United Kingdom
3 Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, Fukuoka, Japan

The Hishikari gold mine, located in Kagoshima prefecture, southern Kyushu, Japan, is a world-class epithermal, low-sulfidation vein-type gold-silver deposit. The mine is composed of three deposits: Honko (Main), Sanjin and Yamada. The high-grade mineralized veins are surrounded by two alteration zones (chlorite-illite zone and interstratified clay mineral zone). The applicability of chlorite geothermometry to the two zones was tested by comparison with fluid inclusion microthermometry and with the chlorite chemical composition of other epithermal and geothermal areas. In addition, the position of the upflow zone at Hishikari was estimated based on the temperature gradient of chlorites. The chemical composition of chlorite and interstratified chlorite-smectite (C/S) at Hishikari were measured using a scanning electron microscope-energy dispersive x-ray spectrometry (SEM-EDS) and an electron probe micro analyzer (EPMA). The formation temperature of chlorite and C/S was estimated using the number of atoms of Al in tetrahedral sites. The calculated temperature of chlorite and C/S ranges approximately from 190° to 280°C. Based on comparison with homogenization temperatures of fluid inclusions from the southeastern part of the Sanjin deposit, the error of formation temperature of chlorite is within several tens of degrees. The application of geothermometry suggests that the difference in the proportion of chlorite layers reflects the formation temperature of chlorite and C/S. Moreover, the estimated formation temperatures of chlorite in epidote and/or prehnite-rich altered rocks are higher than those in epidote and/or prehnite-poor altered rocks. These two groups are distinguished statistically. Thus, the assemblage of chlorite-epidote/prehnite can be an index of a high temperature alteration zonation at Hishikari. Based on the formation temperature gradient of chlorites and comparison of the recognized paleo-water table based on trapping temperature of fluid inclusions, the Sanjin deposit likely represents the hottest part of the upflow zone, which is responsible for the high-grade mineralization at Hishikari.
Laser-induced breakdown spectroscopy (LIBS) analysis applied to indium-bearing minerals and textures at the Baal Gammon polymetallic deposit, Australia

Olivia Mejías González1, Martin Valenzuela2, Brian Townley3, Nathan Fox1, Laura Jackson1, Anita Parbhakar-Fox1

1 W.H. Bryan Mining & Geology Research Centre, Sustainable Minerals Institute, University of Queensland, Australia
2 Department of Mining Engineering, Faculty of Physical and Mathematical Sciences, The University of Chile, Chile
3 Department of Geology, Faculty of Physical and Mathematical Sciences, The University of Chile, Chile

Demand for indium, a critical metal used in the high-technology electronics sector, is predicted to increase by at least 240% by 2050, prompting the need for new resources to be defined. Baal Gammon, located in Queensland, Australia, is an abandoned polymetallic deposit that was mined historically for copper, silver and tin but now potentially represents a world-class indium resource. Understanding the deportment of indium in ore and gangue minerals, as well as defining the textures of indium-bearing phases, must be determined as a first step towards evaluating the geometallurgical characteristics of this critical metal.

In this study, drill core samples (n=18) from the Baal Gammon mine were chemically assessed using a handheld laser-induced breakdown spectroscopy (LIBS) instrument (SciAps Z-300) at the University of Chile. LIBS analyses were conducted on flat drill core surfaces (n=133 areas) to produce rapid, semi-quantitative chemical evaluations using wavelength intensities to generate elemental maps (16×16 raster grid). The technique was able to determine the indium distribution across key ore and gangue minerals including chalcopyrite, pyrrhotite, arsenopyrite, pyrite and cassiterite from a variety of textures including disseminated, veins, replacement and infill massive sulfide.

Based on indium relative intensity, the preliminary results indicate that chalcopyrite is the most endowed mineral, followed by arsenopyrite, pyrrhotite, pyrite and cassiterite. Specifically, chalcopyrite that occurs as an infill massive sulfide texture displays the highest indium. These results indicate: (i) significant potential for using LIBS as a micro-analytical field tool to rapidly screen for critical metals; (ii) chalcopyrite mineralization at Baal Gammon could represent a significant In resource; and (iii) massive sulfide texture may potentially be related to increased indium concentration. Micro-analytical work is ongoing to determine quantitative contents of indium, further if it is present as micro-inclusions or as a solid solution in the chalcopyrite, which will influence future reprocessing options.
Fracture-hosted Fe-Hg mineralization in the Orihuela dolerite, Betic Cordillera, SE Spain

José M. González-Jiménez, Amira R. Ferreira-García
Departamento de Mineralogía y Petrología, Universidad de Granada; and
Instituto Andaluz de Ciencias de la Tierra, Consejo Superior de Investigaciones Ciéntificas (CSIC), Spain

Idael F. Blanco-Quintero, Melanie López-García, Juan C. Cañaveras
Departamento de Ciencias de la Tierra y del Medio Ambiente, Universidad de Alicante, Spain

Rubén Piña, Isaac Corral
Departamento de Mineralogía y Petrología, Universidad Complutense de Madrid, Spain

Mercury has primarily been produced from Hg-bearing ores in: (1) silica-carbonate veins in hydrothermally altered serpentinites, (2) hot-spring sinter related to active volcanism, and (3) sub-aqueous volcanic-related stratabound/stockwork (i.e. Almadén type). An unprecedented vein-style of Fe-Hg mineralization fills fractures in an intrusive dolerite body in the Sierra de Orihuela, in the easternmost portion of the Betic cordiller of SE Spain. This mineralization consists of intergrowths of large (up to 500 μm across) zoned crystals of pyrite [(Ni,Co,FeS_2)], cinnabar (HgS) and hematite (specularite). These metallic minerals are found as massive ores in the central parts as well as disseminations at the margins of fracture-filling veins of epidote ± albite ± calcite ± dolomite ± siderite ± ankerite ± quartz. Pyrite grains located at the proximal contacts with the hydrothermally altered dolerite contain abundant inclusions of epidote ± albite, whereas those located in the central parts of the veins preferentially contain the aforementioned carbonate inclusions. Single-spot laser-ablation ICPMS analysis indicate that pyrite hosting epidote ± albite lack Ag, whereas those hosting carbonates are singularly enriched in Ag (up to ~130 ppm). Mineral-mineral geothermometry indicates formation of hydrothermal epidote via saussuritization of pre-existing plagioclase and amphibole by transformation of pyroxene at the limit of the upper greenschist/lower amphibolite metamorphism of dolerite at <250-300°C. In addition, a careful study of the fluid inclusions hosted in quartz and carbonates indicate the presence of two types of inclusions: (1) biphase (liquid>vapor) and (2) polyphase (liquid> vapor+halite) with identical total homogenization temperatures (Th) of ~180°C at <240 bar, consistent with experimental data indicating coexistence of Ni-Co-rich pyrite and cinnabar at ~200°C. We propose a genetic model implying fault-related fluid circulation of hydrothermal fluids that leached Ca and Mg as well as metals (Ni, Co, Fe) from the dolerite rock while precipitating the ores.
Barite (BaSO₄) is a critical raw material with the major application as a weighing agent in drilling mud. Some of the largest barite deposits in the geological record are spatially associated with large clastic dominant (CD-type) Zn-Pb massive sulfide deposits. In the Selwyn Basin (Yukon, Canada), bedded barite deposits are hosted by black mudstones of the Late Devonian Canol Formation, where barite occurs in the matrix, laminations and nodules commonly in an assemblage with pyrite. The Late Devonian bedded barite also forms part of a larger province extending along western North America’s ancient continental margin. The bedded barite deposits have been variably interpreted, with genesis linked to either lower temperature diagenetic or high-temperature hydrothermal processes. In this study, in-situ isotopic microanalyses by secondary ion mass spectrometry (SIMS) have been used to determine the isotopic composition of sulfur (δ³⁴S) and oxygen (δ¹⁸O) in barite and sulfur (δ³⁴S) in pyrite. The δ³⁴S_{barite} (+37.1‰ to +67.9‰) and δ¹⁸O_{barite} (+8.8‰ and +23.9‰) values represent a substantial offset from Late Devonian seawater sulfate, consistent with precipitation from modified diagenetic pore fluids. The coexistence of the barite with the highly ³⁴S-positive pyrite also demonstrates coprecipitation under progressively sulfate-limited conditions. A similar assemblage containing diagenetic pyrite and barite has been described in the pre-ore assemblage of Late Devonian CD-type deposits nearby in the Selwyn Basin, demonstrating this is the expression of a regional diagenetic process. The diagenetic assemblage formed at the sulfate methane transition zone (SMTZ) where opposing diffusional fluxes of methane (+ barium) and sulfate interact, leading to sulfate reduction coupled to anaerobic methane oxidation (SR-AOM). The replacement of diagenetic barite by other Ba-bearing minerals (e.g. witherite, cymrite and hyalophane) provides further evidence of severe sulfate depletion and conditions under which barite was soluble.
Jurassic shallow epithermal systems from southern Patagonia, Argentina

Diego M. Guido
CONICET and Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Instituto de Recursos Minerales (INREMI), La Plata, Argentina

Kathleen Campbell
Te Ao Marama - Centre for Fundamental Inquiry, Science Faculty, The University of Auckland, New Zealand

Southern Patagonia, Argentina is part of the Jurassic Chon Aike Silicic Large Igneous Province, considered a diffuse back-arc extensional zone related with slow subduction in the Pacific and the presence of a mantle plume related to the breakup of Gondwana and the opening of the South Atlantic Ocean.

Several epithermal deposits and their shallow portions are present in the Deseado Massif province. This metallogenical unit hosts economic gold and silver-bearing, mainly low sulfidation, epithermal deposits spatially and genetically related with the bimodal calc-alkaline volcanic event of the Bahía Laura Complex. In the last five years, 12 mines were operative in the province, together with three advanced projects and several projects under exploration.

The Deseado Massif hosts numerous shallow epithermal systems with well-preserved fossil geothermal areas located in four regional NNW and WNW structural belts. The geological setting at these shallow epithermal systems is characterized by the presence of hydrovolcanic activity, including phreatic and phreatomagmatic breccias forming maar-diatreme volcanic centers, the formation of large shallow lakes (some hypersaline) with restricted fluvial activity, and the intrusion of late acidic extrusive or intrusive domes.

Paleosurfaces are also preserved in these Jurassic shallow epithermal systems with sinters and travertine deposits, as well as a larger quantity of shallow siliceous deposits including cherts and silicified rocks, supporting the overall neutral alkali chloride dominant nature of the hydrothermal fluids. About half of the active epithermal mines are in close spatial relationship (<5 km) with the shallow epithermal geological setting and the presence of paleosurfaces.

Larger and proximal paleosurface features (sinters and phreatic breccias) are associated with mines with larger gold and silver endowment, highlighting the importance of the shallow epithermal systems model as a relevant prospecting tool.
Estimation of gangue mineral percentages from routine drill hole analyses

Scott Halley
Mineral Mapping Pty Ltd, Hawley Beach, Tasmania

Orebodies are not homogeneous. They have spatial variations in metal grades, but also variations in the percentages of silicate and sulfide gangue minerals. These variations influence crushing, grinding and mineral liberation characteristics, power consumption, mill throughput rates, flotation characteristics, recoveries and environmental management of waste rock. Modeling the gangue mineralogy in 3D is an important part of understanding orebodies and making investment decisions. Metallurgical testwork is expensive, and typically carried out on a small number of samples. Ron Berry from CODES (University of Tasmania) developed the Calculated Mineralogy program; this is an excel-based program using the Simplex Algorithm for converting whole rock analyses to estimated weight percent of minerals. This program can be applied to 4 acid digest ICP analyses obtained from commercial assay laboratories. Better understanding of ore type domains and 3D distribution of gangue minerals leads to better sample selection for metallurgical test work. The estimated mineral percentages also provide a proxy for metallurgical properties, with a uniform distribution of data points from every drill hole.

The example shown in this presentation is from a porphyry copper system in North America. This project has a typical porphyry potassic zone, with hypogene upgrading from an advanced argillic overprint. The example will show percentages of quartz, feldspars, white mica, black mica, chlorite, pyrite and anhydrite estimated from 4 acid digest ICP analyses, It will show some validation procedures for checking the results against geochemical alteration plots, and also validation by checking against SWIR data.

Delineating geothermal upflow from surface features: a Waiotapu case study

Ayrton Hamilton1, Kathy Campbell1, Diego Guido2, Micheala Dobson1, Jeff Havig3, Trinity Hamilton2, Laura Penrose1, Bryan Drake1, Michael Rowe1
1School of Environment, The University of Auckland, Auckland, New Zealand
2CONICET-UNLP, Instituto de Recursos Minerales, Calle 64 Esquina 120, La Plata, Argentina
3Department of Earth and Environmental Science, University of Minnesota, Minneapolis, MN, USA

The Waiotapu geothermal system has the largest area of surface alteration of the >20 active high enthalpy geothermal systems in the Taupō Volcanic Zone, New Zealand, with the greatest variety of active and preserved surface manifestations. These surface features have been formed by varied subsurface water-rock interactions, including geothermal upflow and outflow. This study examines a preserved siliceous sinter sheet, known as Northern Waiotapu and dated in this study at 1,111 (±20) years BP, which formed from near neutral alkali pH fluids. The Northern Waiotapu sinter sheet is currently being overprinted by 20 newly active hot springs, with temperatures ranging from 38.4°C to 99.3°C and pH ranging from 2.56 to 8.77, including the first reported high temperature, neutral pH hot springs within the Waiotapu geothermal field. In this study, we examine the textures, trace elemental concentrations, including gold, as well as fluid chemistry of the preserved and active hot springs at the Northern Waiotapu site, and compare these data to Champagne Pool in the main tourist area, to understand the spatial and temporal association of sinter in relation to delineating primary geothermal upflow and potential subsurface mineralization. The chemical, textural and trace elemental results of this study suggest that Northern Waiotapu preserved and active deposits represent geothermal upflow with potential for mineralization at depth. This maybe analogous to the Miocene Favona epithermal deposit in the Hauraki Goldfield, New Zealand.
Alkalic Au-Cu deposits of the Cadia Valley (New South Wales) and Red Chris (British Columbia): unconventional ancient porphyry deposits associated with post-subduction magmatism

Anthony C. Harris, Nicholas Fitzpatrick, Fraser MacCorquodale
Newcrest Mining Ltd, Melbourne, Victoria, Australia

Alan J. Wilson
GeoAqua Consultants Limited, The Valley, Anguilla, British West Indies

David R. Cooke
CODES, Centre for Ore Deposit and Earth Sciences, University of Tasmania, Hobart, Tasmania, Australia

Richard M. Tosdal
PicachoEx LLC, Folly Beach, South Carolina, USA

Some of the world’s largest and highest grade alkalic porphyry Au-Cu deposits occur in the circum Pacific. Silica-saturated alkalic deposits of the Cadia Valley (~50 Moz Au, ~9.5 Mt Cu) in the Ordovician Macquarie Arc (New South Wales) and Red Chris (~13 Moz Au, ~3.7 Mt Cu) in the Triassic Stikinia Arc (British Columbia) share many geological similarities in their environments of formation. These deposits formed in post-subduction, trans-tensional environments after the initial stages of the accretion of remanent arc fragments. Highly oxidized and K-rich ore-related magmas were derived from an enriched mantle source, previously modified by subduction processes. In both cases, their emplacement appears facilitated by deep-crustal, arc normal transverse zones that provided permeable pathways for magma ascent to upper crustal levels (2–3 km depth) favorable for porphyry ore formation.

Deep mineralization in the Cadia Valley and at Red Chris is hosted by sheeted and stockwork quartz – sulfide veins associated with potassic alteration that follows linear intrusive corridors. Mineralized alteration assemblages have limited spatial distribution, extending only a few tens of meters from the alkalic dikes and stocks. Potassic alteration grades laterally into proximal, hematite-bearing propylitic alteration, and transitions upwards from deep K-rich to mineralogically complicated Na-K-Ca metasomatic zones. Zones of mineralization can be up to 2 km in vertical extent, with some of the best developed mineralization positioned at a transition between thick sedimentary successions and overlying volcano-sedimentary pile (e.g. Ridgeway, Cadia Valley, Red Chris – East Zone). This relationship highlights a lithologically controlled permeability important for deposit localization outside of that being created by the repeated emplacement of narrow hydrous magma columns.

Post-mineralization geological processes were critical for the preservation of both porphyry districts. Partially exhumed mineralization was buried beneath regionally extensive basin-fill immediately after porphyry emplacement. Subsequent tectonic burial beneath thrust sheets at Cadia Valley ensured the preservation of its Paleozoic alkalic porphyry deposits.
Antimony mineralizations in the Guadalmez syncline – relationships with Almadén mercury deposits, South-Central Spain

Pablo Higueras, Saturnino Lorenzo
Instituto de Geología Aplicada, Universidad de Castilla-La Mancha, Spain

José María Esbri
Departamento de Geología y Geoquímica, Universidad Complutense de Madrid, Spain

Héctor Campos Rodríguez, Eric Gloaguen
ISTO, UMR 7327, Université d’Orléans, CNRS, BRGM, F-45071 Orléans, France

The Guadalmez syncline is a geological structure located in South Central Iberian Zone, Iberian Hercynian Massif, containing a number of small and decommissioned antimony (Sb) deposits. It is adjacent to the Almadén syncline, site of the World’s largest mercury (Hg) deposits. However, no clear relationships have been established between these different types of deposits, even if both Sb and Hg are frequently associated in many deposits worldwide.

In this presentation we describe the geological context of such deposits. The Sb deposits are hosted by the same geological formation as the most important Hg deposits in Almadén: the Criadero quartzite of Hirnantian age (Lower Silurian). In the Almadén syncline, the most important Hg deposits are strata-bound and consist of disseminated cinnabar (HgS) within the Criadero quartzite. In the Guadalmez syncline, the Sb mineralizations consists of stibnite (Sb$_2$S$_3$) with quartz filling in subvertical veins. At Almadén, the Hg mineralizations have previously been interpreted as related to alkaline volcanism, of phreatomagmatic typology, and mafic composition, strongly affected by a regional alteration replacing the igneous mineralogy with Ca-Mg-Fe carbonates. Together with this alkaline volcanism, and as a relatively minor magmatic event, a tholeiitic episode of (quartz)diabases has also been described in this syncline. This second event is also present in the Guadalmez syncline, and the outcrops of these rocks are always close to the Sb deposits, suggesting a genetic relationship between them.
Trace element systematics of magnetite from the Starra IOCG system, NW Queensland, Australia

Max Hohl, Jeffrey A. Steadman, Jonathan Cloutier, David R. Cooke
CODES (Centre for Ore Deposit and Earth Sciences), University of Tasmania, Hobart, Tasmania, Australia

Shaun L.L. Barker
Mineral Deposit Research Unit, Department of Earth and Ocean Sciences, University of British Columbia, Canada

Iron oxide copper–gold (IOCG) deposits occur worldwide and account for significant amounts of copper, gold and uranium production globally. They are defined by large scale potassic, sodic and iron alteration halos, but the source of the hydrothermal fluids has long been debated. In recent years, it has been suggested that the trace element chemistry of alteration minerals may be used to discriminate fertile from barren hydrothermal systems across a range of deposit styles, including IOCG. This study aims to test the discrimination potential of magnetite at the Starra Au-Cu system, which is hosted in the Eastern Fold Belt of the Mount Isa Inlier, Cloncurry district, Northwest Queensland, Australia. Five deposits occur along the Starra shear, a ca. 6 km-long N-trending fault zone. Mineralization is spatially associated with magnetite-hematite-rich ironstones along the structure, with a gradual increase in magnetite content with increasing depth. Incorporation of trace elements in magnetite is influenced by physicochemical parameters such as temperature and redox, making it an ideal mineral for recording changes in hydrothermal processes. LA-ICPMS imaging of magnetites from distal, proximal and mineralized settings along the Starra shear reveal that magnetite spatially associated with mineralization contains lower V concentrations compared to distal magnetite, suggesting elevated $f_O^2$ conditions in mineralized areas. Estimated magnetite formation temperature based on the $T_{Mg-mag}$ geothermometer combined with $f_O^2$ estimates from trace element data indicate higher temperatures and more reduced conditions during early stages of magnetite formation. Early-stage magnetite at Starra is commonly located at depth, proximal to intermediate-mafic intrusions. Our results indicate the involvement of magmatic-hydrothermal fluids during the formation of the Starra deposits. They also provide new insights into the physicochemical properties and evolution of hydrothermal fluids during the early stages of IOCG-style mineralization at Starra and elsewhere in the Cloncurry district.
Mapping Pb isotope variations across Ireland: from regional metallogeny to deposit-scale fluid flow

Stephen P. Hollis1,2, Aileen L. Doran3, Julian F. Menuge3, David van Acken3, Stephen S. Daly4, Stephen J. Piercey4, Mark R. Cooper5, Richard Unitt6, Oakley Turner7

1Geological Survey Ireland, Haddington Road, Beggars Bush, Dublin, Ireland
2School of Geosciences, Grant Institute, The University of Edinburgh, Edinburgh, UK
3iCRAG and School of Earth Sciences, University College Dublin, Belfield, Dublin, Ireland
4Department of Earth Sciences, Memorial University of Newfoundland, St. John’s, Newfoundland, Canada
5Geological Survey of Northern Ireland, Dundonald House, Upper Newtownards Road, Belfast, UK
6iCRAG and School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland
7iCRAG and Department of Geology, Trinity College Dublin, Dublin, Ireland

Ireland hosts a wide variety of mineral deposit types that span several major regional tectonic events. The nature and extent of metal source rocks, and the pathways along which metals were transferred to sites of ore deposition, are key questions which may be addressed using Pb isotope ratios as tracers. Significant variations in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, model age and $\mu$ (source rock $^{238}\text{U}/^{204}\text{Pb}$) occur systematically across Ireland. Steep gradients in all of these variables outline the Iapetus Suture Zone (ISZ), with all significant Irish-type Zn-Pb deposits located within 50 km of this suture. Lower Palaeozoic basement on both sides of the ISZ host orogenic Au and VMS occurrences. Whereas Gondwanan-affinity crust is associated with high $^{206}\text{Pb}/^{204}\text{Pb}$ values and $\mu$ values of ~9.7 to 9.9, Laurentian-affinity crust is characterized by more juvenile values ($\mu$ ~9.2). Older model ages in SE Ireland occur southeast of the East Carlow Deformation Zone, which is associated with Li-pegmatite emplacement. In SW Ireland, future model ages from sediment-hosted Cu deposits correspond with high $^{206}\text{Pb}/^{204}\text{Pb}$ values and $\mu$ associated with either early uranium enrichment in the Munster Basin or syn-mineralization uranium enrichment and subsequent breakdown. In the Rathdowney Trend of the Irish Zn-Pb orefield, subtle Pb isotope variations have been noted at the deposit scale. At Lisheen, samples from the Lisduff oolite display the least radiogenic isotope ratios along with areas adjacent to normal faults which acted as mineralized fluid conduits. All three Pb isotope ratios increase to the NE across the various orebodies, and continue through the Templetuohy-Bawnmore, Galmoy and Rapla deposits. As larger ore lenses at Lisheen, Galmoy and Navan show the most significant amounts of isotopic variation, Pb isotope analysis highlights the association of larger orebodies with major structural discontinuities and may enable the size of individual ore systems to be assessed at an early prospect stage.
Mafic rocks as a source of Cu, Co and Ni in the Central African Copperbelt

David A. Holwell, Daryl Blanks, Zoe Phelps-Barber
University of Leicester, United Kingdom

Robert Kaemba
First Quantum Minerals, Zambia

The source of metals in the Central African Copperbelt is debated, but generally agreed that redbeds cannot have provided enough metals to account for the known resources. Basement rocks are thought to play a role, but the presence of extensive mafic rocks in the region which contain elevated base metal contents over other crustal rocks, provide an intriguing potential answer to this mass balance problem. Mafic rocks are known to be important, or even major sources of metals in some sediment-hosted Cu systems, e.g. the Yeneena and McArthur Basins, Australia.

Although the deposits and host stratigraphy have been extensively explored and well documented, the volume of mafic bodies within the Copperbelt remains poorly constrained and most likely, underestimated. Modeling of the well-constrained occurrences at Kansanshi, Zambia, has highlighted the morphology, abundance and volume of mafic bodies which have preferentially exploited evaporitic horizons, and occur mostly as flattened pods rather than continuous sills. The intrusions occur at multiple lithostratigraphic depths, are of differing sizes and have been variably altered. Geochemical characteristics indicate that the alteration involved alkali fluids, increasing the bulk K and Na of the mafic rocks, but depleting them in metals such as Cu, Co and Pb.

The association of the mafic rocks with evaporitic strata may be an important control on ore genesis as it is well documented that the ore forming fluids in the Copperbelt were highly saline, and likely sourced, at least in part, from evaporites subsequently destroyed by later metamorphism/hydrothermal fluids. The extensive alkali metasomatism, and associated net losses of metals indicate the mafic rocks are at least in part a metal source in the Copperbelt. Furthermore, we assess the role that highly aggressive fluids in some parts of the region may have also liberated Ni from mafic sources to form deposits such as Enterprise.
Critical metal mobility and recovery from weathered serpentinite and serpentinite skarn tailings from Lord Brassey Mine, Australia and Record Ridge, British Columbia, Canada

Makoto J. Honda-McNeil, Siobhan A. Wilson, Nina Zeyen, Baolin Wang, Colton J. Vessey, Avni S. Patel, Andrew J. Locock
Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada

Ben F. Mililli
BHP Billiton, 171 Collins Street, Melbourne, Victoria, Australia

Connor C. Turvey
Bradshaw Research Initiative for Minerals & Mining, The University of British Columbia, Vancouver, BC, Canada

Jessica L. Hamilton, Daryl L. Howard, David J. Paterson
Australian Synchrotron, Melbourne, Victoria, Australia

Gordon Southam, Jordan T. Poitras, Thomas R. Jones
School of Earth & Environmental Sciences, The University of Queensland, Brisbane, Queensland, Australia

Simon M. Jowitt
Department of Geoscience, University of Nevada, Las Vegas, Nevada, USA

As mineral resources become scarcer, companies are lowering their ore cut-off grades and resorting to exploring deeper underground and in more isolated areas. Incorporating tailings storage facilities as a component of the ore processing circuit can potentially extend the lives of mines and save on future exploration costs.

Ultramafic and mafic mine tailings host resources including first and second row transition metals, such as nickel (Ni), cobalt (Co), and platinum group elements (PGE), whose high value and recovery could serve as a motivator for existing mines to reprocess their tailings. Many of these target metals are initially hosted by olivine, are repartitioned during serpentinization to form sulfides, oxides and alloys, and then are remobilized during weathering to form authigenic carbonates, sulfates and oxyhydroxides. Reprocessing tailings may further provide environmental benefits, including a reduction in waste output and the ability to offset greenhouse gas emissions by enhanced silicate weathering and carbonation reactions.

Here we use powder X-ray diffraction (XRD), scanning electron microscopy (SEM), electron probe micro-analysis (EPMA) and synchrotron X-ray fluorescence mapping (XFM) with X-ray absorption near edge structure (XANES) to demonstrate how critical metals are mobilized to their final sinks. Samples of serpentinite, skarn and weathered tailings from the historical Lord Brassey nickel mine in Tasmania, Australia and weathered outcrops of serpentinite ore from the proposed magnesium mine in Record Ridge, BC, Canada are analyzed and compared. Results from these climatically similar localities indicate the homogenous distribution of Ni within sulfides and increasingly elevated concentrations of Ni in association with iron-oxyhydroxide minerals in progressively more weathered rinds. By developing an understanding of the sinks for metals across the mining lifecycle, we aim to cultivate an economically viable framework for tailings reprocessing that capitalizes on metal mobility during tailings weathering.
Geochronology of porphyry-style hydrothermal mineralization and alteration at Anabama Hill, Delamerian Orogen, South Australia: new insights from zircon U-Pb, molybdenite Re-Os and white mica Rb-Sr ages

Wei Hong1,2,3, Adrian Fabris2,3, Tom Wise2,3, Rian A. Dutch2,3, Sarah Gilbert4

1Department of Earth Sciences, School of Physical Sciences, The University of Adelaide, Adelaide, SA, Australia
2Geological Survey of South Australia, Department for Energy and Mining, Adelaide, South Australia, Australia
3Mineral Exploration Cooperative Research Centre (MinEx CRC)
4Adelaide Microscopy, The University of Adelaide, Adelaide, South Australia, Australia

The Delamerian orogen is the oldest component of the Phanerozoic Tasmanides, and is composed of a Proterozoic continental rift margin overprinted by convergent west-dipping subduction, accompanied by extensive deformation and metamorphism during the Cambro-Ordovician. The Anamaba Hill prospect is one of several magmatic-hydrothermal Cu-Mo±Au occurrences identified in the 1970s in this orogen. Based on logging of legacy drill cores, multiple intrusive rocks have been recognized at Anabama Hill, including granodiorite, monzogranite, diorite and porphyritic dikes, which intruded Proterozoic metasedimentary sequences. This prospect is characterized by intense coarse-grained white mica-pyrite-quartz alteration, which occurs as variable veins, veinlets, clots and breccias. Narrow K-feldspar-quartz veinlets (several cm in width) occur locally in granodiorite, monzogranite and plagioclase-phyric diorite. Weak to moderate epidote-chlorite alteration is developed in this prospect, overprinted by pervasive pyrite-muscovite-quartz alteration that occasionally contains disseminated chalcopyrite and molybdenite. LA-ICP-MS zircon analyses reveal four magmatic emplacement events at Anabama Hill: ca. 485 Ma for granodiorite, ca. 477 Ma for plagioclase-phyric diorite, ca. 470 Ma for monzogranite, and ca. 460 Ma for a porphyritic dike. Two molybdenite separates from the white mica-pyrite-quartz veins yield identical Re-Os ages of ca. 463 Ma. In situ Rb-Sr LA-ICP-MS/MS analyses of white mica crystals from six samples produce a chronological range between 470 and 440 Ma. The older Rb-Sr age of ca. 470 Ma from white mica in veins cutting the diorite is likely an alteration product of the monzogranite underlying the diorite. The 460 Ma of a porphyritic dike mostly overlaps with molybdenite Re-Os age (ca. 463 Ma), and with analytical errors, broadly correlates with white mica Rb-Sr ages of 440-460 Ma. These new chronological data indicate prolonged post-Delamerian magmatic-hydrothermal activity in the region with a ca. 460 Ma age for porphyry-style mineralization. These new data have significant implications on the formation of and exploration for porphyry-style Cu-Mo mineralization in the Delamerian Orogen.

Machine Learning applied to mineral deposits

Shawn Hood
GoldSpot Discoveries Corp., Toronto, Ontario, Canada

Machine learning (ML) is a subfield of artificial intelligence (AI) that includes computational methods to efficiently, objectively and repeatably identify patterns in data. These methods have increasingly been adopted in the science of mineral exploration. Computational techniques such as clustering, classification and automation algorithms are several decades old yet are only recently moving from the use by Earth informatics specialists towards common application by mineral exploration geologists. Applying these methods in a mineral exploration context is not limited to generating drill targets and prospectivity maps; value also comes from producing familiar outputs such as bedrock lithology and alteration maps, extracted logs from drill core, and analysis of ore deposit geometry. By combining ML with domain expertise, mineral exploration and mining workers can achieve objective and repeatable results while retaining familiar traditional work flows.
Europe’s cobalt for electric vehicles: where do we find it and can it meet European demand?

Stefan Horn, Gus Gunn, Evi Petavratzi, Richard Shaw, Jon Naden
British Geological Survey, Nicker Hill, Keyworth, Nottinghamshire, United Kingdom

Electric vehicles (EVs) are a key element in the global movement to reduce carbon emissions and mitigate climate change. Europe is currently the fastest growing market for EVs and is aiming to become the world leader in battery production while also developing its own integrated value chain for EVs. However, European mine production of cobalt, needed for EV batteries, accounted for only 1% of the global total in 2019, with the majority coming from the Democratic Republic of Congo. Our recent study of the cobalt resource potential in Europe has identified 509 cobalt-bearing deposits and occurrences, demonstrating significant potential to increase domestic cobalt production in Europe. Currently, 104 of these deposits are being actively explored for cobalt, 79 of which are located in Finland, Norway and Sweden, where many are related to the Fennoscandian Shield and the Caledonian Belt. Other regions of interest for future development are Ni-Co laterite deposits in the Balkans and Turkey, the Kupferschiefer deposits in Poland and Germany, as well as polymetallic cobalt-bearing vein deposits in several countries across Europe. As cobalt is dominantly a by-product of Cu and Ni mining, information on its grade and deportment is often sparse. Further research is required to refine our geological knowledge on cobalt-bearing deposits and thus improve exploration success and the efficiency of its recovery from various types of ore and mine wastes. As exploration and mine development are time-consuming, it is uncertain whether Europe can expand its cobalt production in time to contribute to the targets for EV sales set by governments and industry.

Host-rock driven compositional and morphological differences in porphyry Cu-Au systems: examples from the Northparkes district, NSW, Australia

Jonathon Hoye
CMOC-Northparkes Mines, Life of Mine and Exploration Department, Parkes, Australia

The Northparkes district, located ~350 km west of Sydney, NSW, hosts at least nine Cu-Au porphyry systems, associated with silica-saturated alkalic quartz monzonite intrusive complexes. Exploration for porphyry mineralization in the Northparkes district is complicated due to the typically narrow pencil-like geometry of ore zones, restricted potassic alteration halos (typically <200 m) and overlapping large-scale regional propylitic alteration zones.

Each of the known deposits within the district displays significant differences in scale, morphology, hydrothermal alteration mineralogy, metal deportment and precious metal ratios. These differences largely correlate with changes in the emplacement setting and composition of the host rock sequence, along with the volume of fertile melt introduced at the time of porphyry formation.

Deposits associated with relatively impermeable felsic to intermediate volcanic hosts, such as E26, typically have nested porphyry geometries with dramatic transitions between ore-grade and background values for ore suite metals, albite – K-feldspar ± white mica dominant alteration assemblages, and high bornite/chalcopyrite ratios. This contrasts with deposits hosted by mafic to intermediate volcaniclastic lithologies like E22 and E48, which display loosely clustered geometries, broader transitions from background to ore grades, alteration assemblages dominated by chlorite – biotite – albite – white mica ± K-feldspar, and intermediate bornite/chalcopyrite ratios. A third end-member composition is more recently recognized with deposits such as GRP314 and MJH hosted within large volume pre-mineral to early syn-mineral monzonite intrusive stocks, displaying more prevalent albite – white mica alteration, diffuse grade boundaries and lower bornite/chalcopyrite ratios.

Common elements exist across the variety of deposit styles encountered within the Northparkes district, including the gross geochemical zonation of pathfinder suite elements such as Mn, As, Te, Se, Sn, W and Mo above and laterally to the porphyry systems. The degree of variance between deposits in a single district highlights the need for flexibility in deposit models at an exploration stage, with targeting driven by an understanding of basement lithology.
Distribution and existing forms of gallium, germanium and indium in sphalerite from Fankou lead-zinc deposit in Guangdong province, China: an ICP-MS study

Zhaobin Hu, Yi Zheng, Pengpeng Yu, Chengming Wang, Xi Chen

a Guangdong Provincial Key Lab of Geodynamic and Geohazards, School of Earth Sciences and Geological Engineering, Sun Yat-sen University, Guangzhou, China
b Guangdong Provincial Key Lab of Geological Process and Mineral Resources Survey, Sun Yat-sen University, Guangzhou, China
c Southern Laboratory of Ocean Science and Engineering, Zhuhai, China

The Fankou giant lead-zinc deposit is located in the northern margin of Quren Basin in northern Guangdong Province, China. The deposit is situated in the center of the Nanling metallogenic belt and occurs within a sequence of the Middle–Upper Devonian and Lower Carboniferous limestone, shale and argillaceous carbonate sediments. Gallium, germanium and indium are enriched and irregularly distributed in sphalerite associated with lead-zinc MVT mineralization. In this paper, the element mapping of rhythmically banded sphalerite from the Fankou lead-zinc mine was carried out by inductively coupled plasma mass spectrometry (ICP-MS), to explore the occurrence and enrichment distribution of Ga, Ge and In. The results show that sphalerite exhibits an obvious element banding structure, enriched in Ga, Ge, Cd, Mn and scarce in In, which is similar to the trace element distribution of sphalerite in typical MVT type lead-zinc deposits. The occurrence of In is different from that of Ga and Ge as it tends to be mineralized in magmatic and volcanic-hosted lead-zinc deposits, which is also consistent with the low In characteristics of MVT lead-zinc deposits. The element mapping results show that the element banding of Ga is consistent with that of Cu, supported by co-varying time-resolved depth profiles. This suggests a close relationship between Cu and Ga, and a possible substitution mechanism of $2Zn^{2+} \leftrightarrow (Cu,Ag)^{+} + (Ga,As,Sb)^{3+}$. Germanium also has an evident correlation with Cu, and its replacement may proceed through the following mechanism: $3Zn^{2+} \leftrightarrow (Ge)^{4+} + 2Cu^{+}$. The study shows how dispersed trace elements can be of great significance to the determination of deposit genesis and the comprehensive utilization of resources.
Geological characterization to identify upgrade potential and enhance mining efficiency

Julie Hunt
Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Tasmania, Australia
Cooperative Research Centre for Optimising Resource Extraction (CRC ORE), Queensland, Australia

Nathaly Guerrero, Karla Morales, Matthew J. Cracknell, Michael J. Roach
Centre for Ore Deposit and Earth Sciences (CODES), University of Tasmania, Tasmania, Australia

Upgrade via screening is a cost-effective way to remove un-economic material early in the mining value chain (MVC). Screening can reduce the amount of material sent for further size reduction and thus reduce the overall amount of energy and water used in the MVC. Exploitation of preferential grade deportment by size (PGDS) is used by this upgrade method as it takes advantage of the propensity for some ores to exhibit preferential breakage which lead to concentration of valuable mineral phases in finer size fractions.

Geological parameters linked to PGDS have been identified through drill core-based detailed logging and data collection using manual (e.g. rebound hardness, portable XRF, magnetic susceptibility) and bench-scale (semi)-automated tools (e.g. hyperspectral mineralogy, down-hole XRF) and include mineralization texture and paragenesis as well as degree of alteration. Knowledge of detailed deportment of valuable phases was obtained from a rapid, low-resolution LA-ICP-MS technique developed by CODES Analytical laboratories. The geological parameters were compared to upgrade potential as measured by Response Ranking (RR), a method developed by CRC ORE to allow comparison of upgrade potential via screening within and between mineral deposits.

Case study samples from porphyry copper vein and disseminated ores show clear differences in RR with vein-related mineralization showing a higher upgrade potential. Samples from intrusion-related gold deposits show that vein paragenesis, vein volume, abundance and spacing, and alteration style and intensity can be significant with respect to RR. Preliminary machine learning-based models demonstrate that geological and geochemical features can be used to effectively model RR and estimate upgrade potential, thus allowing it to be mapped and included in 3D models.

The use of geological characterization data from drill core allows upgrade potential to be identified early and permits its use in deposit evaluation, mine design and planning.
Updating brownfield areas with modern techniques: use of pXRD and hyperspectral SWIR analysis for systematic alteration mineralogy mapping at the VMS-type Aijala-Metsämönttu deposit in southwestern Finland

Irmeli Huovinen, Jenniina Siira, Jaro Kuikka
Geological Survey of Finland

Old mine sites and brownfield exploration areas might be underexplored in the light of new technologies. New data collection and analysis techniques enable a fast way to update existing data as part of exploration target evaluation. Portable X-ray diffraction (pXRD) and hyperspectral measurements for systematic mineralogy mapping was tested as part of the Geological Survey of Finland (GTK) study at the VMS-type Aijala-Metsämönttu deposit. Existing material contains over 500 drill logs and dozens of archived drill cores. Geochemical data is limited to the main ore elements.

Aijala-Metsämönttu is located in the area of Aijala-Orijärvi, part of the Uusimaa belt. A total of 2.3 Mt ore containing 50459 t Zn, 7050 t Pb, 14897 t Cu and 1717 t Au were mined in 1948-1974 by Outokumpu Oy. Ore bodies are subvertical, steeply dipping sulfide lenses. Several deformation events have affected the ore bodies.

X-ray powder diffraction (XRD) is a traditional method for mineral identification. Short-wave infrared (SWIR) reflectance spectroscopy data is used, not only for mineral identification, but also for classification of the chemical changes in minerals. In this study a total of 2623 hyperspectral and 268 pXRD assays were analyzed from 2700 m of core at intervals of one meter and 10 meters, using ASD TerraSpec® handheld spectrometer and TERRA-542 instruments, respectively. Sample preparation included cleaning the drill core and for pXRD, samples were pulverized and sieved to <150 microns before adding to the sample holder.

Major mineral phases can be identified with pXRD, for example, detection of alteration and metamorphic phases caused by zoned Mg-Fe metasomatism. These mineral assemblages are characterized by cordierite, dolomite, mica- and amphibolite mineral group minerals. Compositional variation of chlorite and mica due to alteration is seen from the hyperspectral data. Together these methods form a robust tool to update drill core logging with mineralogical data.
The critical role of magma degassing in sulfide melt mobility and metal enrichment

Giada Iacono-Marziano, Laurent Arbaret
Institut des Sciences de la Terre d’Orléans, UMR 7327 CNRS-Université d’Orléans-BRGM, Orléans, France

Margaux Le Vaillant, Belinda M. Godel, Stephen J. Barnes
CSIRO, Mineral Resources, Kensington, Western Australia, Australia

Research studies provide growing evidence for the presence of fluids within magmatic mineral systems of mafic-ultramafic composition, although these ore-forming magmas are generally considered volatile-poor. We present an experimental study at magmatic conditions that shed light on previously unnoticed physical and chemical processes ensuing from the association between sulfide melt and fluid phases in mafic-ultramafic magmas. Our experimental results show that the association of sulfide melt and bubbles of a fluid phase is independent of the composition of the fluid phase and the mechanism generating it (e.g. magma decompression, or interaction with volatile-rich sedimentary rocks). Depending on the extent of degassing, i.e. the proportion of fluid phase, the implications can vary. When the extent of degassing is limited, the sulfide-fluid association favors the accumulation of the sulfide liquid, by facilitating the coalescence of the sulfide droplets that are attached to the same fluid bubble. This represents a possible solution to the unsolved problem of how sulfide droplets coalesce and are deposited from flowing magma. When the degassing is more extensive, sulfur degasses to the fluid phase decreasing sulfide melt stability. Consequently, the sulfide melt is consumed and its metal content increases, due to the preferential partitioning of metals into the sulfide melt. In our experimental samples, extensive degassing leads to metal enrichment of the sulfide melt, whereas extreme degassing generates platinum group minerals. Accumulation and metal enrichment of sulfide droplets and formation of platinum group minerals are key components necessary for the formation of a magmatic Ni-Cu-Co-PGE ore deposits. The occurrence of a fluid phase in a mafic-ultramafic magma may therefore represent a significant boost for magmatic sulfide ore forming processes, by favoring sulfide melt accumulation and increasing tenors. We show how sulfide-fluid associations preserved in the world-class Noril’sk-Talnakh ore deposits, in Polar Siberia, record the processes that we have demonstrated experimentally.
Mineral potential mapping by using a cell based association approach, a case study from Kajan area, Iran

Zahra Irani
Isfahan University of Technology, Isfahan, Iran

Pooya Asadi Haroni, Hamed Mohammadi
University of Tehran, Tehran, Iran

In this research, the cell based association approach was examined for regional mineral potential mapping in the Kajan area, located in the middle section of the Tethyan metalogenic belt in the main volcanic arc of Iran. This method is based on replacing polygons of geological units with a square cell grid. Each grid’s cell contains a spectra binary code of units that shows their presence (1) or absence (0) within the cell. The mineral potential map highlights favorable cells spectra that includes mineral occurrences. In this research, twelve different evidence layers for the Kajan area were prepared. These layers included five geological units, a fault layer, four alteration units, and two geochemical layers obtained by factor analysis. Each of the layers with categorical variables were translated to a binary variable based on presence or absence. In addition, each of the layers with continuous variables were decomposed to anomaly (code 1) and background (code 0). By analyzing the mineral occurrences in Kajan area, three different spectra code was selected as codes that reflect the favorable cells. The mean distance between the spectra code of each cell and favorable codes was calculated for each cell. The result was a mineral potential map in which each cell contains a value between zero and one. The closer it is to zero, the higher the mineralization potential and vice versa. Comparing the results for the known mineral deposits shows that the cell based association approach is an appropriate way to locate new potential areas for further exploration. For example, the Hashem Abad magnetite skarn deposit, Kalechu epithermal gold-copper deposit and Kuhelakht epithermal silver-gold deposit were all detected in the final mineral potential map. Additionally, one of the critical advantages of this method was that it was possible to optimally control the mineral potential mapping process by the modeler. This is a very important advantage over other methods.

Experimental estimation of carbon dioxide emissions by laterite rocks

Mariam M. Iunusova, Sergey A. Vorobyev, Marina A. Makarova
Lomonosov Moscow State University, Moscow, Russia

The high content of CO₂ (up to 6-10%) characterizes the composition of underground air in the laterite weathering crust profile. The evolution of CO₂ is directly related to organic acids dissolved in soil solutions and flowing through the laterite profile.

In this study, the experimental modeling of laterite and organic acids interaction in different gas atmospheres (air, argon, oxygen) was conducted to determine the amount of CO₂ emission. Laterite samples were selected from the bauxite-bearing area of Telimele (Guinea). Organic acids are citric and oxalic (1:1) with a mixture concentration of 50 mg/l and pH 2. The sample of laterite (5 g, 0.5-1 mm fraction) was mixed with an organic acid solution (laterite:acid = 2.5:1), placed in glass reactors (vol. 0.95 l), and exposed for five days at 24 °C. The CO₂ concentration was measured using a “Dadget” sensor. A bacteriological seeding was also made to consider the biogenic factor.

In summary, we found that ∆CO₂, ppmv was -210 without laterite and acid; -200 with only acid; -830 in air; -960 in argon; -610 in oxygen. This indicates 1) the increase of CO₂ is relatively uniform for all types of gas atmospheres; and 2) the leading cause of CO₂ emission may be bacteria in the laterite samples (70 CFU / 0.65 g of the sample - in 4 days). This study is the initial stage of estimating the amount of CO₂ emission by laterite; it will be continued to determine the total emission volume.
Technological advancements (e.g. rechargeable batteries, mobile phones and hybrid-electric vehicles) are rapidly increasing the demand for rare earth elements globally, but their occurrence in minable deposits is limited. Rare earth elements (REEs) can be a by-product of certain mining operations and consequently accumulate in waste streams. The Queensland Government’s New Economy Minerals Initiative, in a collaboration with the University of Queensland, is challenging the management of mine waste by seeking opportunities to define mine waste as a resource of new economy metals to supplement growing metal demands.

Phosphate Hill, in north western Queensland, has been manufacturing ammonium phosphate fertilisers from the phosphate mine and ore processing facility since 1999. Annually, Phosphate Hill produces approximately 1 million tonnes of fertilisers and 1.4 million tonnes of phosphogypsum and slime waste. These are stored in stacks and dams on site or used as backfill, volumes of waste are continually increasing. A field campaign to assess economic rehabilitation options targeted phosphogypsum waste stacks (n = 29) and slime dams (n = 20). Assay results show the REE concentrations are higher in the slime waste (average all REEs: 812 ppm) compared to the phosphogypsum waste (average all REEs: 396 ppm). Specifically, Dy, Nd, Er, Eu, Gd, Ho and La concentrations are more than double average crustal abundance. MLA and XRD results suggest that fluorapatite is the host of REEs in both waste streams, with high concentrations from 49.7 wt.% to 63.2 wt.% (average: 54.1 wt.%). LA-ICPMS analysis of fluorapatite confirmed the deportment mode of these REEs assisting in the selection of appropriate metallurgical recovery techniques.
Evaluating hydrothermal episodicity and rates of ore-forming processes at the seafloor

John W. Jamieson, Christopher G. Galley, Natalie C. McNeil, Dennis Sánchez Mora
Department of Earth Sciences, Memorial University of Newfoundland, Canada

Jenny M. Maccali, Desiree L. Roerdink
Department of Earth Science, University of Bergen, Norway

The rates of formation of volcanogenic massive sulfide deposits can be evaluated by investigating actively forming hydrothermal deposits on the modern seafloor. High-resolution bathymetric mapping combined with U-series geochronology enable deposit accumulation rates to be constrained. However, to accurately interpret these data, it is necessary to understand if venting has been continuous or episodic over the history of the deposit’s formation. The results of monitoring of several vent fields over years to decades indicate relatively stable, continuous venting over these timespans. However, many vent fields are older than 10,000 or even 100,000 years, and dating of sulfide-rich samples using U-series disequilibrium techniques can provide insights into both the age and the continuity or episodicity of venting. For example, dating of over 70 samples from the active TAG mound, on the Mid-Atlantic Ridge, has produced an age spectrum that suggests the mound has been active for only 5,000 to 10,000 years during its 50,000 year history. However, the number of samples collected and dated at TAG is exceptional. In most cases, because of the challenges associated with collecting rock samples from these deposits, the often much lower number of dated samples results in age distributions that contain significant time gaps that could be interpreted as evidence of either continuous or episodic venting. Evaluating episodicity will not change the results for calculations of overall average deposit growth rates but can have a profound effect on the assessment of potential instantaneous deposit growth rates and metal fluxes. In this talk, we will discuss our current understanding of the ages and growth rates of seafloor hydrothermal deposits and present a statistical approach for evaluating the probability of episodicity from the determined age spectrum for several hydrothermal vent fields on the seafloor.

Using multidimensional mineral systems-based predictive models to tackle the growth challenge facing the mining industry

Nicole Januszczak
BHP

In the future, most significant discoveries will be under cover in technically challenging environments that render them blind to our current exploration toolkit for predicting and detecting ore deposits. To address this, we will rely increasingly on insights from predictive modeling and machine learning. An integral part of this approach will be to identify and test datasets we do not routinely use, and to apply datasets in new and innovative ways. Picking the right ground to explore is key to successful exploration. Considerable value lies in front-end loading predictive modeling at global and regional scales to ensure that we are exploring for world-class deposits in the best mineral belts in the world and not exploring for the best deposit in a mediocre belt. A mineral systems approach to exploration is predicated on an understanding of the critical processes that need to align in space and time for an ore deposit to form, providing critical grounding for predictive models. The opportunity in this space is truly extraordinary. At BHP we have learned from our success in petroleum exploration in remote and deeply buried (deep underwater) environments. With application of systems thinking and the development of technology to image the petroleum system, they can now take an area the size of London, and with the light from eight lampposts, essentially draw a map of the city. We are being similarly challenged in minerals. As with petroleum systems, mineral systems operate across all scales, spatially and temporally, enabling an adaptation from two dimensional prospectivity maps that focus largely on the shallow parts of a mineral system to holistic predictive models which are based on a comprehensive understanding of mineral systems in four dimensions, deep into the Earth system and back in time.
Ghost towns as markers of the resilience conditions along extractive frontiers

Yona Jébrak
Department of Urban Studies and Tourism, Université du Québec à Montréal, Canada

Michel Jébrak
Department of Earth and Atmospheric Sciences, Université du Québec à Montréal, Canada

Noémie Fayol
IMT Mines Alès, France

Since the Neolithic revolution, mining occurs in the semiperiphery of civilizations. It provides wellness outside the core urbanized zone and exchanges knowledge, money and infrastructures against minerals. The dynamic establishment of such a pattern goes throughout the development of an extractive Frontier moving outward from the economic core zone. However, extractive Frontiers may fail and leave ghost towns and remnants of mining workings. Thousands of ghost mining towns (GMT) have occurred on all continents since the Chalcolithic times.

The study of mining ghost towns allows to distinguish several extractive Frontiers based on their environment. Most of them are in unpopulated highly inhospitable or poorly accessible environments such as hot and cold deserts, and high mountain ranges. Three types could be recognized along the mining cycle: (1) GMT where, although it was claimed that resources were exhausted, mining development failed early due to lack of capital and/or knowledge. These GMT are often related to gold rushes in the 19th century (Macetown, New Zealand; Bannack, Montanna; Kolmanskop, Namibia) and especially abundant in Australia and West America. (2) GMT occurring during or after the production, due to disruptive innovations that make the product outdated such as asbestos, micas, saltpeter and sulfur (Atacama, Sicilia); this is the probable future for petroleum-related cities. (3) GMT occurring after mining that had exploited most of the ore for decades: this has occurred several times since the Bronze age, especially in Central Europe and southwest Asia, but also since the 20th century (Hashima Island, coal, Japan; Joutel, copper, Canada).

What are the elements that make or fail the resilience of a Frontier mining town? What lessons can we learn from history? How can they help understand the resilience of mining territories and communities? The presentation will offer an insight from history through the lens of resilience thinking.
The West African Exploration Initiative (WAXI): 15 years of research for development

Mark Jessell
The University of Western Australia, Crawley, WA, Australia

The WAXI Team

The fifteen-year AMIRA Global Project P934 ‘West African Exploration Initiative’ (WAXI), now heading to its fourth phase, has the dual aims of scientific research focused on increasing our understanding of the tectonic and regolith settings of ore deposits, and the development of the research and training capacity of West African geological surveys and universities. We describe the drivers for the WAXI initiative, as well as key research and capacity building outcomes. The WAXI project is a public-private partnership that has brought together seventy of the principal stakeholders in the domain of minerals exploration in West Africa:

- The government surveys and departments of mines of eleven West African states (Burkina Faso, Ghana, Guinea, Ivory Coast, Liberia, Mali, Mauritania, Niger, Sierra Leone, Senegal and Togo)
- Seven West and South African universities (from Burkina Faso, Côte d’Ivoire, Ghana, Mali, Senegal and South Africa)
- Thirty-four international mining companies
- Researchers from twelve European and Australian research institutions
- AMIRA Global, an independent association of minerals companies that develops, brokers and facilitates collaborative research projects
- NGOs based in Burkina Faso, Ghana and Luxembourg
- A professional training center based in Burkina Faso
- National research and aid agencies in South Africa, France and Australia

This initiative demonstrates the significant research and development impacts that can be achieved when the different stakeholders in the minerals sector (industry, academia, government and non-government organisations) work together to achieve their diverse goals.

The WAXI project in numbers:

- 12 countries
- 73 partners over 15 years
- 95 Postdoc, PhD, Masters and Honors Projects, two-thirds of them African
- 110 International Publications
- 650 GB exploration geoscience database
- 1800 person-days of technical training in West Africa
- 650,000 km² of geophysically constrained geological mapping
Geological distance

Mark Jessell¹, Vitaliy Ogarko², Uli Kelka², Guillaume Pirot¹, Mark D. Lindsay¹,²
¹Mineral Exploration Cooperative Research Centre, CET, The University of Western Australia, Australia
²CSIRO Australian Resources Research Centre, Kensington, Western Australia, Australia

Mineral system analysis demands a combination of the understanding of fundamental geological processes and the multiscale structural, stratigraphic and tectonic setting at the time of mineral deposit formation. In many complexly deformed terranes, our understanding of the former far outweighs our understanding of the latter. Analyzing the spatial relationships between known mineralization and geological ‘features’ such as faults, intrusions and specific stratigraphic units has traditionally used a Euclidean metric to describe distance. Developing alternate distance metrics that better represent geological processes may allow us to better constrain which processes, and which features, define a specific mineral system. We have modified the map2loop/map2model codes to deconstruct a part of the 1:500,000 Interpreted Bedrock Geology Map of the Hamersley Region of Western Australia. The graph-based analysis used in this study demonstrates the potential for incorporating additional geological information to define non-Euclidean distances in a Mineral Systems context. For clarity, distances here were calculated between stratigraphic units, but could also be between faults and units, or mineral deposits and faults. In the example here we have used electrical resistivity as a proxy for fluid flow as the mathematical descriptions are similar, and in the future, we could also add capacitance/storage capacity for elements. A closer coupling to geological processes and age relationships is also possible using this method, as different faults, or generations of faults, can be weighted according to their relevance during the active stages of mineralization. We could also draw upon empirical relationships between width of damage zones (and hence permeability) and fault length to modify graph element weighting. This study demonstrates the potential for using non-Euclidean approaches to estimating distance in regions of complex geology.

The significance of phyllic alteration at the E26 porphyry Cu-Au deposit, Northparkes, NSW, Australia

Rhiannon Jones, David R. Cooke, Angela Escolme, Lejun Zhang
ARC Research Hub for Transforming the Mining Value Chain, University of Tasmania, Hobart, Australia

Jonathon Hoye
CMOC-Northparkes Mines, Life of Mine and Exploration Department, Parkes, Australia

E26 is an alkalic porphyry Cu-Au deposit in the Northparkes district, New South Wales, Australia. Multiple quartz monzonite porphyry intrusions are associated with sulfide mineralization and hydrothermal alteration. Phyllic alteration at E26 is particularly complex and variable, with several generations that overprinted potassic and propylitic alteration assemblages. Some phyllic alteration events were associated with Cu sulfides, whereas others are barren. Understanding paragenetic relationships between mineralized and barren phyllic assemblages has important implications for geometallurgy and exploration in the porphyry environment.

Detailed observations and micro-analysis of drill core samples from E26 reveal six paragenetic stages of phyllic alteration. Phyllic alteration occurred in transitional (T1, T2), late (L1, L2, L3) and post-mineralization stages (Pm 1). Phyllic paragenetic stages associated with Cu sulfides (chalcopyrite ± bornite) include T1, L2 and L3. The T1 alteration assemblage includes albite – white mica – chlorite ± quartz with bornite. The L2 assemblage is defined by quartz – white mica with chalcopyrite ± bornite within vein halos around quartz – anhydrite – bornite ± chalcopyrite veins. L3 is fault-related and includes white mica – anhydrite – chlorite ± albite with chalcopyrite. The T2, L1 and Pm1 assemblages lack Cu sulfides. The T2 assemblage contains hematite – white mica – chlorite ± albite. The L1 assemblage consists of white mica – quartz – pyrite ± calcite. Pm1 is a fault related assemblage of quartz – white mica – pyrite. The phyllic paragenetic stages associated with Cu sulfides are more prevalent at depth, whereas the barren phyllic paragenetic stages are more common in the shallow parts of the system.
Spodumene pegmatites: linked crystallization and fluid expulsion, and their implications for ore formation

David Kaeter, Julian F. Menuge
iCRAG and UCD School of Earth Sciences, University College Dublin, Belfield, Dublin, Ireland

Renata Barros
Geological Survey of Belgium, Royal Belgian Institute of Natural Sciences, Brussels, Belgium

In 2020, more than half of the world’s lithium was sourced from lithium pegmatites of the Li-Cs-Ta (LCT) family, making them key resources for the rapidly growing electric vehicle battery market. These pegmatites also hold significant resources of tin, which has a promising application in high energy-density anode materials for rechargeable batteries, and tantalum, which is essential in microelectronics amongst numerous other uses. Reading the mineralogical record of LCT pegmatite deposits can inform deposit models, mineral exploration and geometallurgy. Our research focuses on a belt of LCT pegmatites located along the eastern margin of the late-Caledonian S-type Leinster Batholith, southeast Ireland. These LCT pegmatites are hosted by a major regional shear zone and are part of a tin-lithium province that stretches subparallel to the Iapetus suture from Europe through Nova Scotia, Canada, to North and South Carolina, USA. We investigated crystal chemical zoning in muscovite, cassiterite and columbite-tantalite using petrography, scanning electron microscopy and laser-ablation ICP-MS chemical mapping. The zoning patterns record that pegmatite rare-element mineralization resulted from an interplay of magmatic crystallization, metasomatism and hydrothermal processes. Late-stage metasomatic alteration led to partial resorption of early minerals including the lithium ore-mineral spodumene, followed by dispersion of lithium and other rare elements into country rocks, mostly into dark mica. This dispersion led to formation of geochemical halos around the pegmatites. Whole-rock ICP-MS analysis of country rocks within a few metres of pegmatites demonstrates that inventories and grades of some elements are comparable to those in the pegmatite itself. This highlights the potential to use country-rock lithogeochemistry and mica composition as geochemical vectoring tools, and the possibility that new mineral processing methods may allow mining of pegmatite halos.

Geological modeling using MWD data

Lance Karlson, Myra Keep, Mark Jessell, Guillaume Pirot, Mark Lindsay
School of Earth Sciences, University of Western Australia

Lance Karlson, Dr Ilnur Minniakhmetov
BHP Geoscience

Measure While Drill (MWD) datasets from blast-hole drill rigs in the Pilbara region, Western Australia have been used to generate detailed geological models. These data include measurements such as rate of penetration, torque, weight on bit and rotation speed, with blast holes spaced between 5 and 8 m apart. Normalized MWD datasets have been processed using a range of mathematical techniques, with the aim of rapidly determining stratigraphic and structural boundaries. Trial datasets have been used to model folding, faulting and intrusions that were unable to be interpreted from conventional assay and downhole geophysics datasets due to the wider spacing of exploration drill holes. Trial MWD models have been validated by in-pit mapping, and work is planned to quantify the geological uncertainty of the models.

MWD data have previously been an unreliable data source for geological modeling due to outliers caused by variables such as different drillers, drill rigs and drill bits. This project demonstrates that there is potential to use the data for modifying stratigraphic and structural wireframes in mining operations. The high-resolution geological models also provide the potential to interrogate and assess our understanding of structural events that led to the generation of orebodies in the Pilbara.
Constraining Cu-Co mineralization in the Zambian Copperbelt using accessory minerals: rutile, monazite and apatite

Jamie Kelly, Steve Roberts
National Oceanography Centre, European Way, Southampton, United Kingdom
University of Southampton, University Road, Southampton, United Kingdom

Simon Tapster
British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, United Kingdom

Richard Herrington, Jamie Wilkinson
Natural History Museum, Cromwell Road, South Kensington, London, United Kingdom

Constraining the genesis of stratiform, sediment-hosted Cu-Co deposits within the Central African Copperbelt is challenging owing to the complex deformation history of the Lufilian Orogeny. Timing of mineralization in the region is contentious, with competing hypotheses for restricted, 50-million-year mineralization during the Lufilian Orogeny or for more prolonged, multi-episodic mineralization encompassing early diagenetic through to post-orogenic timing. Most of the geochronology cited as evidence are Re-Os molybdenite ages, supporting a 540-490 Ma mineralization event or mixed sulfide Re-Os ages suggesting mineralization older than 800 Ma. However, these older ages lack robustness, contain large errors and used a bulk sulfide methodology now questioned by the scientific community in its validity. Meanwhile, the molybdenite ages, whilst more robust, may be considered to constrain remobilization of pre-existing sulfides and cannot explain geochronology obtained via U-Pb uraninite, Pb-Pb Cu-Fe sulfide or Re-Os carrollite ages that fall outside the Lufilian timeframe. Accessory alteration minerals such as apatite, monazite and rutile are under-represented in the Copperbelt and thus may provide fresh perspectives on this ongoing debate.

This study focuses on the Mindola North deposit within the Zambian Copperbelt. Samples were analyzed petrographically before being processed by TESCAN TIMA analysis and quantitative SEM-EDS methodologies to establish a paragenetic framework and textural associations between phases. Numerous examples of rutile were found in association with chalcopyrite-bornite occurrences within the matrix, displaying mutual growth textures. Quantitative-EDS reveals a strong vanadium enrichment in the rutiles with multiple substituting elements including Nb, Fe, Cr, Si, K, Ca, Mg and Cu. Layer-parallel quartz-dolomite-albite veins contain macro crystalline chalcopyrite-bornite-carrollite, with many containing coarse fluorapatite crystals. Chalcopyrite is observed nucleating around monazite, suggesting a post-monazite timing for Cu mineralization. The application of in-situ LA-ICP-MS U-Pb rutile, dolomite and monazite geochronology may help to further constrain the timing of Cu-Co mineralization in the Zambian Copperbelt.
Cu-Au porphyry fertility of Lachlan Orogen intrusions - insights from apatite inclusions in zircon

Lillian A. Kendall-Langley  
Centre for Exploration Targeting, School of Earth Sciences, University of Western Australia, Crawley, Australia  
RSC Mining & Mineral Exploration, West Perth, Australia

Anthony I. S. Kemp  
Centre for Exploration Targeting, School of Earth Sciences, University of Western Australia, Crawley, Australia

Chris J. Hawkesworth  
School of Earth Sciences, University of Bristol, Wills Memorial Building, Queen’s Road, Bristol, United Kingdom

Malcolm P. Roberts  
Centre for Microscopy, Characterization and Analysis, University of Western Australia, Crawley, Australia

The volatile budgets of arc-related magmas are critical to their potential for porphyry copper ore formation, however magmatic abundances of volatile species such as H₂O, S, Cl and F are challenging to assess. This study trialed a novel approach to collecting magmatic volatile data - the analysis of apatite inclusions trapped within zircon. Apatite incorporates the volatile species Cl, F, S, OH and CO₂ into its crystal lattice alongside numerous process sensitive trace elements, making it an ideal recorder of volatile behaviour in evolving melts. Major and trace element data were collected from apatite inclusions and host zircon crystals by micro-analytical techniques to investigate the volatile inventories of Cu-Au porphyry intrusions of the Macquarie Arc and associated unmineralized I-type granitic suites of the Lachlan Orogen (eastern Australia). Drawing upon recent advancements in apatite-melt F-Cl-OH exchange modeling, a method was devised to estimate magmatic concentrations of Cl and F from the composition of apatite inclusions in zircon. Melt Cl and F concentrations calculated by this method indicate that Cu-Au porphyry bearing magmas of the Macquarie Arc were not enriched in Cl or F relative to unmineralized I-type magmas of the Lachlan Orogen. Within individual intrusions, melt Cl and F concentrations typically decrease with magmatic differentiation and this is attributed to the partitioning of Cl and F into exsolving aqueous fluids, a process favoured by magmatic volatile saturation at greater crustal depths. Additionally, Sr/Y, La/Sm and Cl/F ratios in apatite inclusions, and Eu/Eu* ratios in zircon are useful in discriminating Cu-Au porphyry intrusions of the Macquarie Arc from related barren intrusions. These results demonstrate the volatile and petrogenetic information stored in apatite inclusions in zircon can provide unique insights into the abundances and behaviour of magmatic volatile species.
New applications of hyperspectral sensing for geological exploration using multivariate statistical methods

Gabor Kereszturi, Rupsa Chakraborty, Cecilia Rodriguez-Gomez
Geosciences, School of Agriculture and Environment, Massey University, Palmerston North, New Zealand

Hyperspectral remote sensing measures reflected light from objects at hundreds to thousands of narrow but contiguous spectral bands. Hyperspectral data covering Visible-Near Infrared (VNIR; 350–1000 nm) and Shortwave Infrared (SWIR; 1000–2500 nm) can detail light absorption features related to molecular bonds of Fe-, Mg-, Al-, Mn-, CO$_3$ and -OH containing minerals at microscopic, hand-specimen and landscape scales. However, the spectral "oversampling" of the electromagnetic spectrum can also result in high dimensionality and collinearity that requires band reduction and selection approaches to be applied in the analytics. Traditional approaches take advantage of spectral oversampling by analyzing absorption depth, position and morphology/symmetry and match absorption profiles with a spectral library for mineral recognition. However, multivariate statistical analysis can enable new applications using hyperspectral data.

This contribution reviews recent hyperspectral remote sensing applications combined with multivariate statistical analysis to develop new toolkits for mineral exploration for epithermal and mesothermal (orogenic) gold mineralization, and geological mapping of active volcanoes and geothermal fields. Our case studies include hyperspectral data analyzed through either image classification or regression methods and complemented by Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy, Inductively Coupled Plasma Mass Spectrometry and portable X-ray Fluorescence analysis to ground truth and to provide support for our interpretations. Image classifications show improved accuracies to delineate surface hydrothermal alteration zones and lithological changes over bare land on both Mt Ruapehu volcano and Waiotapu geothermal field. By calibrating laboratory- and airborne hyperspectral images with geochemical data, we also develop new image classification and regression approaches to map the distribution of metal-induced plant stress over both Waiotapu geothermal field and East and Central Otago orogenic gold mineral exploration sites for the first time. These techniques can provide new qualitative and quantitative methods to describe hydrothermal alteration, compositional changes, and potentially map elemental distribution associated with underground mineralization.
Lithium and boron geochemistry of melt inclusions from rhyolites parental to lithium-bearing salars of Nevada, USA and Southern Puna Plateau, Argentina

Regina M. Khoury, Celestine N. Mercer, Albert H. Hofstra
U.S. Geological Survey, Denver, CO, USA

Julie Roberge
Instituto Politécnico Nacional, Ciudad de México, MÉXICO

Lithium is a high-demand, energy-critical element used in lightweight rechargeable lithium-ion batteries that is produced primarily from pegmatites and brines in arid, closed lacustrine basins. The Central Andean salars of the Altiplano-Puna Plateau contain the largest global resource of lithium brines. Clayton Valley, Nevada is the only current producer of lithium brines in the United States. Locally-exposed rhyolite tuffs have been proposed as a lithium source for these lithium brines and salars. These two regions exemplify distinctive magmatic-tectonic regimes for salar lithium enrichment.

Our goal is to characterize pre- and post-eruptive lithium contents, better constrain sources of lithium, and investigate the role of varying tectonic regimes in the generation of magmas parental to economic lithium brines. We analyzed the abundance and isotopic composition of lithium and boron in quartz-hosted melt inclusions and pumice glass from Miocene-Pliocene rhyolite tuff outcrops surrounding Clayton Valley, Nevada, USA and Salar Hombre Muerto, Catamarca, Argentina. Preliminary LAICPMS and SIMS data indicate that rhyolites from Hombre Muerto are relatively Li-rich (30-1100 ppm Li, 70-130 ppm B) compared to those from Clayton Valley (~20-480 ppm Li, 10-150 ppm B). Lithium depletions and large positive d^7Li fractionations between melt inclusions and pumice glass suggests some melts lost up to ~50% lithium upon eruption. In contrast, boron isotopic compositions show a narrow range (~6‰ to 2‰ d^{11}B) in both melt inclusions and pumice glass from Clayton Valley, indicating that d^{11}B provides a robust constraint on rhyolite-source provenance. Melt inclusions and pumice glass from Hombre Muerto show a similarly narrow range in boron isotopes, but are distinctly lighter (~17‰ to -12‰ d^{11}B), indicative of a significant crustal source component.
Trace elements in apatite record differentiation processes in Sept-Iles mafic layered intrusion

Marie A. Kieffer, Sarah A.S. Dare*

Department of Applied Sciences, University of Quebec in Chicoutimi (UQAC), Chicoutimi, QC, Canada

*Canada Research Chair in Geochemistry Applied to Ore Deposits

Olivier Namur

Department of Earth and Environmental Sciences, KU Leuven, Heverlee, Belgium

Apatite is a weathering-resistant mineral that occurs in most igneous, sedimentary, metamorphic and hydrothermal rocks. Trace element chemistry in apatite is typically used to track magmatic processes, as a provenance indicator for sedimentary studies, and has the potential as an indicator mineral for mineral exploration. Although several processes may influence the trace element content of apatite during and/or after its crystallisation (such as reaction with trapped liquid, subsolidus reequilibration), it is not yet known if their influence on apatite chemistry is significant. To better constrain these processes, we have determined the chemical composition of apatite (by electron microprobe and LA-ICP-MS) throughout the whole sequence of the mafic layered intrusion of Sept Iles (Québec, Canada) where the process of differentiation (fractional crystallization, magma mixing, contamination and immiscibility) are well-constrained based on whole rock, mineral chemistry (e.g. plagioclase, olivine, pyroxenes and iron-oxides) and Sr isotopes. Apatite occurs as a cumulus phase at the top of each megacyclic unit, but only one of those is mineralized (Critical Zone, up to 27% vol. apatite) with evidence for liquid immiscibility (e.g. Fe-rich and Si-rich silicate melts). In this study, we demonstrate that apatite in the Sept-Iles layered intrusion not only records the bulk fractional crystallization (increase of Th, U, Ba andREE) but that the crystallization of apatite, when in a sufficient amount, may also fractionate the REE content of the melt, affecting subsequent apatite REE patterns. Furthermore, apatite can indicate magma contamination using Pb, Th and U. Intercumulus apatite is distinguished from cumulus apatite using different elements, such as a higher Cl or V content. Improving our understanding of apatite chemistry from layered intrusions – which are important hosts of Fe-Ti-V-P resources – enlarges its use as an indicator mineral for exploration purposes.
Distal signatures of the Bingham porphyry Cu-Au-Mo mineralization in carbonate wallrocks

Michael Kirschbaum Zhaoshan Chang
Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado, USA

Paul Agnew, Adam Pacey
Rio Tinto, Bundoora, Victoria, Australia

Phillip Nickerson, Andrew Sasso
Rio Tinto, Salt Lake City, Utah, USA

Kim Schroeder, Kathleen Gundy
Rio Tinto Kennecott, South Jordan, Utah, USA

The Bingham Canyon porphyry Cu-Mo-Au occurrence (Utah, USA) is a highly productive mineral system with an extensive hydrothermal alteration halo. Such systems likely cause subtle, far-field alteration patterns which may be useful in vectoring toward the system center. This study presents initial results from our investigation into the effects of this hydrothermal system on two laterally extensive carbonate units, the Jordan and Commercial limestones, by analyzing the trace elements of calcite in veins and in adjacent carbonate wall rocks, and compares the findings with signals from other systems such as the Candelaria Cu-Au deposit, Chile.

Bingham Canyon comprises a multi-phase sequence of Eocene igneous rocks emplaced within a folded and thrusted Paleozoic carbonate and siliciclastic sequence, producing proximal Cu-Mo-Au porphyry-style mineralization and adjacent Cu-Au skarn deposits in carbonate host rocks, mainly in the Jordan and Commercial beds. Outboard from the porphyry-skarn zones (~0.5-2.5 km), there are Pb-Zn-Ag vein and carbonate replacement orebodies, and even more distal (~7-9 km), sediment-hosted Au deposits.

A series of vein and wall rock samples were collected beginning at the Bingham Canyon open pit and extending 17 km to the W-SW along a transect terminating at the sub-economic Stockton porphyry system. LA-ICP-MS analysis was completed on vein and wall rock calcite. Preliminary analysis reveals a decreasing trend in Fe, Mg, Ba and several REEs from the Bingham Mine outboard to a distance of ~3-5 km, while Mn and Zn display an increase to about 2 km distance before dropping off to background levels ~4 km outboard. These initial findings are based on 12 samples which we will corroborate through further LA-ICP-MS analysis of additional samples along the transect to produce a robust spatial dataset.
External controls in metal endowment and styles of mineralization in andesitic volcanoes – example from the Štiavnica stratovolcano, Slovakia

Peter Koděra, Alexander Kubač
Department of Mineralogy, Petrology and Economic Geology, Comenius University in Bratislava, Slovakia

Jaroslav Lexa
Earth Science Institute, Slovak Academy of Sciences, Bratislava, Slovakia

Bertrand Rottier
Département de Géologie et Génie Géologique, Université Laval, Québec, Canada
Centre de Recherche Sur la Géologie et l’ingénierie des Ressources Minérales (E4m), Québec, Canada

Oscar Laurent
Institute of Geochemistry and Petrology, ETHZ, Zürich, Switzerland

The Štiavnica andesitic stratovolcano in the Western Carphatians hosts both intrusion-related deposit (Pb-Zn stockwork, Cu-Au skarn-porphyry) as well as extensive systems of intermediate- to low-sulfidation Au-Ag-Pb-Zn-Cu epithermal veins. Magmas and all the deposits were sourced from an upper crustal (~1 to ~3 kbar) reservoir that was active more than 3 My. According to thermobarometric studies, LA-ICP-MS and EMPA data from melt inclusion and SHRIMP U-Pb dating of associated intrusive and volcanic rocks, these deposits were formed during periods of reservoir cooling when the residual melt reached fluid saturation. The LA-ICP-MS data on fluid inclusions from all these deposits showed increased B, As, Sb concentrations indicating that the main source of fluids was a magmatic vapor contracted to liquid during ascent from the reservoir, which is consistent with microthermometry data. Most fluid inclusions show a relatively constant composition (including metals) and high Cs contents advocating exsolution from an evolved interstitial melt of roughly constant composition. This is consistent with the stable composition of evolved melt inclusions in rock-forming minerals (e.g. B/Rb, Rb/Cs), representing the residual melt in an upper crustal reservoir during different stages of magmatic activities. The fluids were continuously exsolved and accumulated, but liberated during periodic tectonic events. These include migration via contraction fractures (Pb-Zn-Cu stockwork in granodiorite), ring fractures and shear zone induced by a sector collapse of the volcano (early Au-Ag-Pb-Zn-Cu veins), along with porphyry stocks and ring dikes as a precursor of a caldera collapse (Cu-Au skarn-porphyries), and faults of a resurgent horst uplift (late Ag-Au-Pb-Zn-Cu veins). Ore precipitation was triggered by mixing magmatic and meteoric water (stockwork), boiling of decompressed fluids (early veins), cooling of contracted vapor affected by early fluid heterogenization (skarn-porphyries) and mixing+boiling (late veins). Our results show that external factors, rather than fluid compositions, primarily control the different metal endowment of these deposits.
Ammonium associated with the Favona epithermal gold deposit in the Coromandel Peninsula, New Zealand: its distribution and source

N. Kieran Kristoffersen, Keiko Hattori
Department of Earth and Environmental Sciences, University of Ottawa, Ottawa, Ontario, Canada

Mark P. Simpson
GNS Science-Wairakei Research Centre, Taupō, New Zealand

The Hauraki goldfield in the Coromandel Peninsula hosts numerous epithermal low-sulfidation vein-type deposits including Martha (>6.7 Moz Au, >42.1 Moz Ag) and Favona (>0.6 Moz Au, >2.36 Moz Ag) deposits, and the recently discovered Wharekirauponga (WKP; 0.42 Moz Au of indicated and 0.72 Moz Au inferred resource) prospect. The gold deposits occur in extensively altered andesitic to rhyolitic volcanic rocks of late Miocene to Pliocene ages that overlie the basement of Jurassic metasedimentary rocks. Alteration formed adularia, illite, mixed-layered illite-smectite, chlorite, kaolinite, smectite, calcite and albite. Some deposits / prospects also have ammonium minerals identified by short-wave infrared (SWIR) reflectance spectroscopy. This study determined the quantity of ammonium in rocks, its distribution, and host minerals, as well as investigated nitrogen isotope compositions to evaluate the source. Leaching experiments using a 2N KCl solution show that over 90% of ammonium is in mineral structures. Ammonium concentrations show broad positive correlations with LOI (0.6-16.3 wt%), and K₂O (1.3 to 8.0 wt%), suggesting it is hosted by hydrous K-bearing minerals. This is consistent with samples with high ammonium showing significant absorption of Al-OH in the SWIR spectra. At Favona, SWIR identified ammonium (990-10117 ppm) in wall rocks extending ~100 m from veins. The footwall illite-altered zone contains 990-4301 ppm ammonium. In the hanging wall, within 100 m of the mineralization in the mixed layer illite/smectite alteration zone, ammonium values range from 1827-10117 ppm. Beyond this 100 m zone in the hanging wall, ammonium contents are low, 107-301 ppm, which are too low to be detected with SWIR. δ¹⁵N values range from +0.5 to +7.9 ‰ (n=54), suggesting that nitrogen in ammonium is sourced / derived from either the metasedimentary basement or sediments intercalated with volcanic rocks.
Analyzing environmental and social incidents in mining: implications for raw material criticality assessments

Konstantin Kühnel; Philip Schütte; Gudrun Franken
Federal Institute for Geosciences and Natural Resources (BGR)

Vanessa Bach; Matthias Finkbeiner
Technische Universität Berlin, Institute for Environmental Technology

The availability of responsibly produced raw materials has become an intensively discussed topic. One approach to indicate risks in mineral supply chains is the method of criticality assessment, which determines criticality as a combination of the probability of supply disruptions and anticipated harm related to these disruptions. A systematic integration of environmental and social aspects into criticality assessment methods does not yet exist.

This study presents a dataset of social and environmental incidents in the mining sector from 2013 to 2018. The distribution of these incidents was analyzed with regards to systematic relationships on their occurrence and impacts as a contribution to further developing criticality assessment methods. The dataset builds on a keyword search in a large commercial database on global mining sector intelligence. Overall, 256 incidents were analyzed, categorized by country, affected mining stage and cause. A semi-quantitative magnitude rating differentiates the incidents by their economic, environmental and social impacts. While 50% of all incidents are associated with five countries alone, the general distribution between environmental and social issues as well as magnitude ratings is more or less even on a global scale. Major differentiation can be observed when analyzing specific countries, mining stages, or causes.

Significant insights of the analysis are the need to consider the overall number of incidents in a country in relation to the national mining intensity, which may give a different image of the risk potential. Furthermore, a tendency is indicated that environmental issues gain importance relative to social issues in industrialized and high-income countries. While the development stage is associated with very few incidents compared to the production stage, it shows considerable higher average magnitude ratings. As the development of new production capacities will influence supply security in the medium and long term, this emphasizes a more detailed assessment of the development stage.
Indium bearing mineral occurrences in fractionated magmatic-volcanic complexes of Herberton mineral field, northeast Queensland, Australia

Avish Kumar, Ioan Sanislav, Paul Dirks
Economic Geology Research Unit (ERGU), College of Science and Engineering, James Cook University, Townsville, Queensland, Australia

Henrietta Cathey
Central Analytical Research Facility (CARF), School of Earth and Atmospheric Sciences, Queensland University of Technology, Brisbane, Queensland, Australia

Indium is recognized as a critical metal due to its limited supply and high demand in the manufacture of LCD, touchscreens and solar panels. Indium is sourced as a by-product from Cu and Zn ores and occurs in a variety of mineral systems, including the VMS, porphyry, skarn, SEDEX, polymetallic veins, and magmatic-hydrothermal deposits. The magmatic-volcanic complexes of the Herberton mineral field primarily host Sn mineralization that is related to fractionated granites of the O’Briens Creek Supersuite. The later phases of Sn mineralization are associated with polymetallic veining that occasionally forms thick veins (up to 2m) of massive sulfides. In this study, the Baal Gammon massive sulfide deposit and the Isabel polymetallic vein deposit were studied for their indium contents and distribution within the sulfide ore system. The mineralogy of the two deposits were analyzed using SEM and a detailed study was carried out using a field-emission electron probe microanalyzer (FE-EPMA). Mineral maps of sphalerite show zonation at the Baal Gammon deposit. No internal zonation was observed at the Isabel deposit. However, our findings show that indium occurs mainly in stannite and as a refractory phase in sphalerite, where it is coupled with copper and cadmium. High indium values in chalcopyrite, which forms the bulk ore at Baal Gammon, are related to the exsolution of zinc bearing stannite and sphalerite minerals. These exsolutions are common throughout the deposits and form the main host for indium. Stannite in these systems formed at the expense of cassiterite dissolution. Apart from indium, stannite associated with galena has high silver content. The physicochemical parameters that governed during indium, tin and base metal mobilization were also modeled and show that the mineralized fluids were initially reduced and acidic and evolved towards more alkaline and reduced conditions as mineralization processes progressed.
Thermal infrared-active vibrational modes of spodumene and their relationship to Fe-content

Carsten Laukamp, Monica LeGras, Bobby Pejcic
CSIRO Mineral Resources, Kensington, Western Australia, Australia

Spodumene (LiAlSi2O6) is the predominant Li-host mineral in LCT-pegmatites and it is well established that the presence of Fe significantly reduces the value of Li resources. Previous studies have shown that spodumene can contain considerable amounts of Na+, Fe3+, Al3+ and Li+ mainly in M1 and M2 sites. This paper describes the diagnostic thermal infrared (TIR)-active vibrational modes related to spodumene in natural mineral assemblages where spodumene is associated mainly with quartz, feldspar, di-octahedral mica and tourmaline. All the aforementioned silicates produce primary reststrahlen bands in the 8000 to 12000 nm wavelength range. TIR reflectance spectra were collected using a Fourier-transform infrared spectrometer (FTIR) coupled to an integrating hemisphere on 102 samples sourced from the drill core C3DD024 of the Greenbushes Li deposit (Australia), noting that these contained various amounts of spodumene.

The 8000 to 9500 nm wavelength range shows significant overlaps between reststrahlen features of the spodumene and the associated silicates. However, the 9500 to 12000 nm wavelength region is less impacted by the associated silicates, resulting in a characteristic spectral signature of spodumene-bearing samples in this wavelength range. The broad reflectance peak centered at around 10750 nm can be attributed to closely spaced fundamental Si-O stretching vibrations. A shift of the wavelength position of the 10750 nm reflectance peak (and the neighboring troughs) to shorter wavelengths can potentially be attributed to a decrease of the mean ionic radius of the M1 and M2 cations, because the ionic radius impacts on the tetrahedral chain angle and Si-O bond lengths and, therefore, the Si-O stretching vibrations. This potentially offers the opportunity for estimating the Fe-content in spodumene by means of hyperspectral TIR field or drill core reflectance spectrometers, which are readily available to the critical minerals industry.
Tellurium nanoparticle formation as evidence of tellurium biogeochemical cycling

Ella Lausberg, Barbara Etschmann, Rahul Ram, Joël Brugger
School of Earth, Atmosphere and Environment, Monash University, Clayton, Victoria, Australia

Owen Missen
School of Earth, Atmosphere and Environment, Monash University, Clayton, Victoria, Australia
Geosciences, Museums Victoria, Melbourne, Victoria, Australia

Xi-Ya Fang
Monash Centre for Electron Microscopy, Monash University, Clayton, Victoria, Australia

Tellurium (Te) is a critical raw material (CRM) used in new technologies including green energy generation. The transition to carbon neutral technology will increase our exposure to Te through two main factors: (1) our use of cadmium telluride solar panels for cleaner electricity and their subsequent decommissioning and recycling; and (2) the expansion of copper mining operations that will produce larger amounts of Te as a byproduct. Tellurium is a concern for environmental contamination with the increased usage due to the acute toxicity of some soluble forms of Te (notably the tellurite and tellurate anions) for both microbes and humans. The most common mode of microbial resistance is the production of Te nanoparticles (NPs) through a detoxification mechanism, involving chemical reduction of the toxic soluble Te oxyanions to NPs of native tellurium. Here we show the presence of Te NPs in regolith samples, found in varying concentrations and size distributions from two sites in northern Mexico and four sites in south-western United States of America using Single Particle ICPMS. The concentration of Te NPs in soil exceeds 1000 ppm in areas contacting Te-rich veins at Moctezuma, Sonora, Mexico. In general, the Te NPs are larger in regolith close to the mineralized veins, with size decreasing with distance. Results show Te is a mobile element in the environment, generally dispersing away from Te-bearing mineralization. Tellurium NPs contribute to Te mobility and function as a short-term sink in soils, especially around Te-rich sites. In particular, the Te NPs in distal locations are likely to be produced by bacteria, as Te NPs are generally reactive and would be expected to rapidly oxidize, leaving only oxidized Te. The presence of distal Te NPs thus provides strong evidence of biological cycling of this CRM.
Study of magmatic sulfide melt infiltration into an unconsolidated silicate mush - analogue modeling

Margaux Le Vaillant, Stephen J. Barnes
CSIRO, Mineral Resources, Kensington, Perth, Australia

Anja Slim, Andrew Coward
School of Mathematics, Monash University, Victoria, Australia

Anton Maksimenko
Australian Synchrotron, IMBL Beamline, Victoria, Australia

Important questions remain regarding physical processes in the genesis of magmatic Ni-Cu-PGE sulfide ores. Some of the biggest unknowns relate to the balance between gravitational and surface tension forces controlling interactions between sulfide and silicate magmas. We are investigating this balance through analogue modeling.

Analogue experiments were focused on coalescence and infiltration/percolation of sulfide liquid within an unconsolidated crystal mush. The analogue components were chosen considering relative densities, viscosities and interfacial surface tensions. The three components studied are 1) silicate melt (the magma), 2) silicate crystals (olivine), and 3) liquid sulfides. Perfect analogues for these three components were determined as: 1) olive oil, 2) HDPE plastic beads simulating a pile of touching crystals, and 3) salted water. Experiments were imaged in 3D with two spatial resolutions using first a medical X-ray computed tomography system (0.5 mm voxel size), and then using the IMBL beamline at the Australian Synchrotron (50 µm voxel size).

Results show three different behaviors in function of the proportion of water (i.e. sulfide melt) present in the system: 1) Less than 5% water in the introduced ‘slurry’ results in small amounts of coalescence for droplets in close proximity but no infiltration, 2) More than 10% water in the ‘slurry’ results in coalescence of droplets followed by infiltration through the crystal pile (plastic beads), and 3) over 20% of water, results in very rapid coalescence followed by percolation and even fracturing of the bead pile, with the water creating its own path and accumulating at the bottom of the experiments. These results demonstrate that coalescence and sulfide percolation/infiltration can be expected to occur readily in natural systems, especially within a non-coherent crystal mush. A rigid silicate crystal framework might be essential for matrix sulfides.
Integrated socio-technological approaches for adaptive land-uses in mining economies: a Greek case study

Amelia Lee Zhi Yi  
Centre for Mined Land Rehabilitation, Sustainable Minerals Institute, The University of Queensland  
Glen Corder, Anna Littleboy  
Sustainable Minerals Institute, The University of Queensland  
Guillaume Echevarria  
Soil and Environment Laboratory, INRAE, Université de Lorraine  
Agnès Samper  
LabEx RESSOURCES21, Université de Lorraine

Social considerations on mine closure in mining operations management are increasing in importance yet often inadequately addressed through superficial consultative process with the community. Exploring the interconnectedness of the social and scientific paradigms between community, government and corporate stakeholders in mine closure, particularly in the beginning stages of the mine life cycle, is critical for assessing the feasibility of novel and innovative post-closure land use options.

We introduce a case study exploring socio-technological considerations affecting the adoption of nickel agromining in Greece as a potential technology in mine closure and rehabilitation. The aim of the study is to understand the sentiments and motivations of the identified stakeholder groups in upscaling and implementing agromining initiatives. Sixteen scoping interviews were conducted with technical, commercial and regulatory stakeholders in Greece, where the technology will be deployed, and in France, where the technology is developed.

Findings are categorized into social, economic and technical drivers and benefits, barriers and risks. It was observed that stakeholders are driven by the job creation potential of agromining but limited in their understanding of the technology due to its relative commercial infancy. Subsidies and commercial investments that drive economic considerations are restrained by potential regulatory barriers of an untested technology. Meanwhile, the green nature of agromining increases technological novelty but is unseated by concerns in ecological unbalancing of the local biodiversity.

While further reflection on the dataset will be performed, this study provided an overview of stakeholder sentiments, outlines the overlap of motivation between stakeholder groups, and suggests that the lack of knowledge of the methodology is a major barrier to the implementation of agromining in Greece. Future testing of this hypothesis will be performed through analysis of web-scraped text and media elements to determine how knowledge dissemination affects trends of interest in stakeholders through time.
Expanding the Au-Ag hybrid VMS model to include high sulfidation deposits

David V. Lefebure
School of Earth and Ocean Science, University of Victoria, British Columbia, Canada

Volcanogenic massive sulfide (VMS) deposit models are a critical targeting tool for the exploration geologist at regional and property scales. They provide information about tectonic settings, key commodities, host and associated rocks, formation environment, ore minerals and their textures, and more recently, mineral systems. There are five well known models – bimodal mafic (Noranda), bimodal felsic (Kuroko), mafic back arc ophiolite (Cyprus), pelitic-mafic or siliciclastic mafic (Besshi) and siliciclastic felsic (Iberian Pyrite Belt, Bathurst Camp). The discovery of the rich Eskay Creek gold-silver deposit in British Columbia, Canada in 1989 (3.35 Mt grading 46.0 g/t Au and 2224 g/t Ag) led to widespread recognition of another VMS deposit type that incorporated aspects of both low sulfidation epithermal and massive sulfide mineralization. It has been identified as a precious metal-rich, hybrid bimodal felsic deposit type. Seafloor discoveries of precious metal-rich hydrothermal systems have played a major role in understanding of this environment for VMS deposits on land. For example, research has shown that mineralization with low sulfidation epithermal characteristics can form at greater water depths than initially predicted. It also identified high-sulfidation, copper-rich systems with elevated precious metal contents. At the same time more deposits on land were being subdivided into low sulfidation (e.g. Dolly Varden, British Columbia and LaRonde, Quebec) and high sulfidation (e.g. Boliden, Sweden; Bousquet 2, Quebec) VMS mineralizing systems with epithermal characteristics. This has led the author to adopt a broader hybrid VMS deposit model that incorporates both epithermal and VMS characteristics and recognizes that the host rocks can include felsic or mafic volcanics and sediments. The differences between these six VMS deposit models are highlighted in classification systems that incorporate key properties used by field geologists and others.
Critical elements from the Tapolcsány Formation (Uppony Mts, NE-Hungary)

Lívia Leskôné Majoros, Sándor Szakáll, Ferenc Kristály
University of Miskolc, Faculty of Earth Science and Engineering, Institute of Mineralogy and Geology, Miskolc-Egyetemváros, Hungary

In 2020, the European Commission published the new Study on the EU’s list of Critical Raw Materials. In that list, 30 critical raw materials are included. In our study, we focus on these critical elements, especially on natural graphite and geochemically related elements of graphitization: titanium, niobium, vanadium and rare earth elements (REE). Rock samples were collected from outcrops along the Rágyincs valley (Uppony Mts, NE-Hungary), exposing the Tapolcsány Formation (Silurian, deep sea facies). The collected samples are black colored, intensely deformed and schistose fine-grained siliceous black schists.

The samples were investigated with polarizing petrographic and ore microscopy (OM), scanning electron microscopy (SEM-EDX), X-ray powder diffraction (XRD), X-ray fluorescence spectrometry (XRF), inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectroscopy (ICP-AES).

The samples have a metamorphic texture based on OM and SEM observations. The matrix consists of microcrystalline quartz grains. In the matrix, 20-40 µm sized microcrystalline mica plates (muscovite, muscovite with Na and phengite) can be found, often with high vanadium content.

Many accessory minerals are also detected. The main Ti minerals, anatase and rutile are often found in the deformed zones with low Nb and V content. The REE-containing minerals are xenotime, monazite-(Ce) grains and goyazite-gorceixite mixed crystals with low Ce and Nd contents. The main Zr-bearing mineral, zircon is also frequently present in the samples, linked to the deformed zones.

Graphite can be observed as μm-sized flakes scattered in the matrix and as 100-300 µm-sized grains (with low S content) arranged in the direction of deformation. Graphite also often forms aggregates of a graphite-sericite-quartz mixture. Graphite is unable to be detected in XRD analyses directly from the diffraction curves due to its low quantity and main peak overlapping with quartz peaks. However, its direct quantification is possible by Rietveld refinement.
Deciphering fluid origins in the Paleozoic iron oxide-Cu-Au (IOCG) deposits, East Junggar, NW China: constraints from noble gases and halogens

Pei Liang, Yuling Xie
School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing, China

Huayong Chen
Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, China

Represented by the Laoshankou, Qiaoxiahala and Heijianshan deposits, the northern margin of East Junggar and the Yamansu belt of East Tianshan are two important potential belts for Paleozoic iron oxide Cu-Au (IOCG) mineralization in NW China. All IOCG deposits in these two regions formed in a basin inversion setting (dying back-arc basin) and show significant two-stage mineralization, i.e. Fe-oxide and chalcopyrite (-gold). In this study, we used halogen (Cl, Br and I) and noble gases (Ar, Kr and Xe) from fluid inclusions of quartz and epidote as reliable tracers to track the fluid sources and evolution of these deposits. The results (in mole ratios) obtained by a MAP 215-50 noble gas mass spectrometer through an UHV extraction line at the Noble Gas Laboratory at the Australian National University (ANU), showed that three different fluid end members are mainly involved in the mineralization processes of these Paleozoic IOCG deposits: (1) a magmatic-hydrothermal fluid, with I/Cl, Br/Cl and \(^{40}\)Ar/\(^{36}\)Ar ratios of 16.3×10^{-6} to 18.0×10^{-6}, 1.03×10^{-3} to 1.06×10^{-3} and 352 to 437, respectively; (2) surface-derived bittern brine derived from seawater evaporation, with highest Br/Cl ratios of 1.53×10^{-3} to 1.80×10^{-3}, and I/Cl and \(^{40}\)Ar/\(^{36}\)Ar ratios of 77.1×10^{-6} to 87.7×10^{-6} and 672 to 883, respectively; and (3) basin brine or formation water modified by organic-rich strata through water-rock reaction, with highest I/Cl ratios of 477×10^{-6} to 26,301×10^{-6}, low Br/Cl ratios of 0.39×10^{-3} to 1.28×10^{-3} and \(^{40}\)Ar/\(^{36}\)Ar ratios of 288 to 510. The obvious multi-stage mineralization and involvement of Ca-rich hypersaline non-magmatic brines with variable origins in the Paleozoic iron oxide Cu-Au deposits in the Central Asian Orogenic Belt (CAOB) resemble the characteristics of other IOCG type deposits in the world. These findings further suggest that non-magmatic fluids dominate the formation of IOCG deposits in the basin inversion setting.
Alternatives for geochemical modeling in time and space

Mark Lindsay
CSIRO Mineral Resources; CET, School of Earth Sciences, The University of Western Australia; and
ARC Centre for Data Analytics for Resources and Environment

Sandra Occhipinti, Václav Metelka
CSIRO Mineral Resources

Some forms of geoscientific modeling do not adequately represent the richness of knowledge that can be extracted from geochemical data. The predictive capability of tools such as 3D and mineral prospectivity modeling suffers due to a range of difficulties that preclude the use of geochemistry. At the regional scale, sparse and clustered sampling results in large regions of no or missing data that cannot be directly input into a spatial model without careful consideration. Interpolation is commonly used to provide complete spatial coverage as required by most modeling algorithms, but doing so adds substantial uncertainty in regions distal to sample locations where interpolated values may be completely misrepresented. Algorithms allowing incomplete coverage offer paths to compensate for no or missing data include: (1) masking (where ‘data-less’ regions are removed from the model); (2) interpolation of no data regions; or (3) imputation of missing data. At the mine scale, data density is thankfully high, but issues arising from too much data are encountered. Ore targeting at this scale has benefitted from traditional pairwise and ternary analyses; however, these are generally non-spatial; thus, geochemical analyses in the mine generally focus on grade. Clustering and classification techniques can assist in integrating geochemistry with rock properties that relate to complete coverage datasets like geophysics. These machine learning approaches can reveal subtle and unexpected relationships indicating alteration, texture and structure, which is necessary to understand the distribution of mineralization. Interpolation of these clusters in 3D or as inputs to mineral prospectivity modeling is thus advocated to gain additional insight. Additionally, isotope geochemistry (Sm-Nd, Hf-Lu, S) is under-utilised in regional models despite clear links to the spatial representation of magmatic sources, mantle processes and tectonic evolution. Valuable insight is gained using alternative methods to create integrated geochemical models.
Sources of sulfur in the Erdaohezi Pb-Zn-Ag deposit, NE China: constraints from in-situ sulfur isotope analyses

Yanrong Liu
School of Earth Science and Resources, Chang’an University, Xi’an, Shaanxi, China

Robert Moritz
Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Anne-Sophie Bouvier
Institute of Earth Sciences, University of Lausanne, Lausanne, Switzerland

The Erdaohezi deposit, discovered in 1980, is a Pb-Zn-Ag deposit, which is located in the middle part of the Derbugan metallogenic belt, NE China. Pyrite is ubiquitous in the deposit, and in order to understand the sources of sulfur and the evolution of the ore-forming conditions, we have studied the ore textures and the in-situ sulfur isotopic compositions of pyrite using secondary-ion mass spectrometry (SIMS). Five generations of pyrite have been identified in this deposit (Py1 to Py5). The sulfur isotopic compositions of the different generations of pyrite show large variations of δ34S values, ranging from -9.80‰ to 5.03‰. Py1, Py2 and Py3 display relatively narrow ranges of δ34S values generally around 0‰ (Py1=1.07 to 4.97‰, Py2=0.54 to 5.02‰, and Py3=-1.91 to 5.03‰), which are markedly close to that of the mantle, indicative of a magmatic source. By contrast, Py4 and Py5 are characterized by negative δ34S values (Py4=-4.18 to -0.19‰, and Py5=-9.60 to -3.28‰). Two processes can be invoked to explain these negative δ34S isotopic compositions: (1) sulfur in the pyrite is derived by leaching of wall rocks with negative δ34S values; or (2) pyrite was precipitated from fluids with a high oxidation state. Considering that the wall rocks in the Erdaohezi deposit are Mesozoic volcanic rocks with δ34S values of 1.5 to 6.3‰, the negative sulfur isotopic compositions of Py4 and Py5 are attributed to oxidized hydrothermal fluids. A previous study has shown that the initial hydrothermal fluid in the Erdaohezi deposit had a relatively low oxygen fugacity characteristic of a reduced environment, and that the ore-forming fluids gradually evolved from primary mantle fluids to meteoric water. Therefore, we conclude that the negative sulfur isotopic compositions of Py4 and Py5 reveal the input of oxidized meteoric water during the latest mineralization stages.

A novel method of age constraint on Mississippi Valley-type Pb-Zn deposits by palynomorphs: a case study of the Changdong deposit in China

Yingchao Liu
Institute of Geology, Chinese Academy of Geological Sciences

Mississippi Valley-type (MVT) Pb-Zn deposits serve as the world’s primary supply of Pb-Zn resources. However, the age constraint of MVT Pb-Zn deposits has long been a big challenge due to the lack of minerals unequivocally related to ore deposition, which can be used for radioisotopic dating. We show sporopollens can provide useful chronological information on the Changdong MVT Pb-Zn deposit in the Simao basin, Sanjiang belt, West China. Internal sediments host the Pb-Zn ores in the Changdong deposit in paleo-karst caves of meteoric origin. Sphalerite and galena occur as replacements for carbonate minerals and void infillings in the internal sediments. The relations suggest that the Pb-Zn mineralization occurred after the deposition of the internal sediments. A palynological assemblage mainly composed of angiosperm pollen dominated by Castanea, Quercus and Carya and fern spores dominated by Polypodiacaeae, Pteris, and Athyriaceae was identified. These pollen and spores place the ore-hosting sediments and the Changdong paleo-karst in the early to middle Oligocene. Consequently, the Changdong Pb-Zn deposit must have formed after the early Oligocene (~34 Ma). Together with the geological characteristics, these age constraints indicate that the Changdong Pb-Zn deposit is a paleo-karst-controlled MVT deposit related to fold-thrust systems in the Sanjiang belt. The Changdong deposit is similar to other MVT Pb-Zn deposits in the northern part of the Sanjiang belt, extending this Pb-Zn belt 500 km further to the South. Results presented here highlight the potential of sporopollens in dating the age of MVT deposits related to paleo-karst formation in young orogenic belts.
Towards unlocking the value of detailed characterization data for comminution and geometallurgical modeling

Pia Lois-Morales  
Department of Mining Engineering, Faculty of Mathematical and Physical Sciences, University of Chile  
Julius Kruttschnitt Mineral Research Centre, Sustainable Minerals Institute, The University of Queensland

Catherine Evans  
WH Bryan Mining and Geology Research Centre, Sustainable Minerals Institute, The University of Queensland

Dion Weatherley  
Julius Kruttschnitt Mineral Research Centre, Sustainable Minerals Institute, The University of Queensland

Comminution is an important stage in mineral processing as it liberates valuable from non-valuable minerals. Geometallurgy applied to comminution seeks to identify relationships between the geological characteristics and the comminution response as measured in standard tests (e.g. Bond work index) to develop predictive geometallurgical models. However, a large number of metallurgical tests is required for a reliable geometallurgical model, which can be challenging to obtain with limited resources. Also, the detailed rock characterization data cannot always be fully utilized because the comminution tests are performed on large composite samples which contain many rock types. Moreover, current comminution tests do not allow the value of the geological data to be unlocked as they are designed to represent the material’s response under specific breakage conditions.

The mechanical properties of rock particles (e.g. rock strength), which are critical parameters for the newest comminution models, are highly dependent on the mineralogy and texture of rocks, but are less dependent on the comminution machine operation. This work explores the relationship between detailed quantitative characterization data and the mechanical properties of particles using an experimental comminution device.

Comparing the quantitative ore characterization information with the mechanical properties reveals that the elongation of the grains, the physical properties (e.g. elastic moduli) of individual minerals and the contrast between these properties for adjacent grains could be used to predict the mechanical breakage properties of rock particles. Nonetheless, other variables, such as grain size and porosity, cannot be discounted and require further investigation. This work demonstrates that the mechanical properties of particles at different sizes are related to rock characteristics to the extent where this information could be directly applied to plant prediction. The further development of these findings can help improve the definition of geometallurgical domains for comminution, considering a better use of the geological information.
Metallogenic processes of the Tongchang Cu-Fe deposit: constraints from the in-situ S isotopes

Yan Luan
School of Earth Science and Resources, Chang’an University, Xi’an, China
Laboratory of Mineralization and Dynamics, Chang’an University, Xi’an, China

Xiaohui Sun
School of Earth Science and Resources, Chang’an University, Xi’an, China

The Tongchang deposit is one of the most representative Cu-Fe deposits in the Qinling orogenic belt, which is an important part of the Central Orogenic Belt of China. It is mainly composed of an Fe deposit in the lower part and a Cu deposit in the upper part. Sulfide assemblages are mainly pyrite, pyrrhotite and chalcopyrite in the lower part and are mainly chalcopyrite and pyrite, without pyrrhotite in the upper part. In-situ S isotopic analyses indicate that sulfides in the lower part (+8.66‰ to +10.9‰ for chalcopyrite, +8.85‰ to +11.0‰ for pyrite, and +7.93‰ to +9.28‰ for pyrrhotite) are isotopically lighter than those in the upper part (+9.75‰ to +13.1‰ for chalcopyrite and +9.22‰ to +13.9‰ for pyrite). The δ34S∑ value in the early ore-forming hydrothermal fluid is estimated to be +10.6‰ using the Pinckey-Rafter method, and that in the later ore-forming hydrothermal fluid is +12.3‰. These results suggest that the S of the Tongchang deposit is sourced from both mantle S (0±3‰) and contemporaneous seawater S (+26.5‰ to +35.5‰ in Early Paleozoic). Thermochemical sulfate reduction (sulfate reduction by hydrocarbons or Fe2+) played an important role in the processes of seawater sulfate reduction. The magmatic-hydrothermal fluid with enrichments of volatiles (including F-, Cl- and CH4) and S mixed with seawater S, and extracted Fe and Cu from the spilite of the Guojiagou Formation. The early ore-forming hydrothermal fluid formed the Fe mineralization in the lower part. With the precipitation of magnetite and sulfide, the later ore-forming hydrothermal fluid migrated upward and produced the Cu mineralization in the upper part.

Textures and mineralogy of the Ohakuri fossilised hot spring sinter, Taupō Volcanic Zone, New Zealand

Barbara Lyon, Kathleen Campbell, Michael Rowe, Ayrton Hamilton
School of Environment, The University of Auckland, New Zealand

The Ohakuri fossilized hydrothermal system, Taupō Volcanic Zone, New Zealand, is an extensive (~25 km²) area of hydrothermal deposits and alteration, with numerous preserved paleo-surface features, including siliceous sinters, acidic alteration and epithermal veins. Sinter deposits, derived from deep circulating alkali-chloride waters, outcrop over 7 km². They are up to 6 m thick in surface exposures, and up to 15 m thick in drill core. The well-preserved hydrothermal system is hosted in the Ohakuri Ignimbrite (~290 ka). Other lithologies displaying varying degrees of hydrothermal alteration include several pyroclastic, volcanic airfall, lacustrine and alluvial deposits. Analysis of sinters and other silicified features record evidence of several phases of activity caused by fluctuations in the water table in a system that was long-lived, with recent reports indicating hydrothermal activity over ~170 ka. The Ohakuri system has been extensively explored for epithermal mineralization since the early 1980s, but an inferred upflow zone in the area of Central Stream produced only subeconomic gold that is low-grade and disseminated. The numerous, widespread hot spring deposits at Ohakuri have been largely under-utilized as an exploration tool in previous studies. The preserved macroscopic and microscopic textures infer formation at a range of spring discharge temperatures (~100°C to ambient), including near-vent geysersite, mid-apron microbial mats, and distal marshes. Such features have been used to constrain possible vent locations (i.e. upflow zones) and contribute to a more thorough understanding of the system’s history. Variations in fluid chemistry have also been preserved, in the widespread occurrence of kaolinite as well as corroded sinter and spicular microstromatolites like those that form in acid-sulfate conditions. By utilizing the information gained from mapping the extent and types of preserved lithofacies, a reconstructed paleoenvironment from the time of active sinter deposition may elucidate upflow zones and evolution of surface environments of the Ohakuri system.
Evolution of the Ertsberg Pluton, Ertsberg-Grasberg Mining District, Papua, Indonesia

Jacob Makis, Mark Cloos
Department of Geological Sciences, University of Texas at Austin, Austin, Texas, USA

The Ertsberg Pluton is the largest (>15 km$^3$) and youngest (3.1-2.75 Ma) igneous body within the Ertsberg-Grasberg Mining District of Papua, Indonesia. It is associated with ore-grade Cu-Au mineralization in the form of four large skarns (Ertsberg, Big Gossan, Dom, and giant Ertsberg East Skarn System: GBT/IOZ/DOZ/MLZ/DMLZ) and a localized zone of porphyry style mineralization. Ertsberg rocks are clinopyroxene + titanite bearing and range in composition from monzonite or monzodiorite (± quartz), but overall, the pluton is relatively equigranular and homogeneous. This apparent homogeneity led to the interpretation that the bulk (> 95%) of Ertsberg was emplaced as a single batch of magma that underwent fractionation. To constrain the emplacement and evolution in detail, a suite of 63 samples was analyzed for major and trace geochemistry, 31 of which underwent LA-ICPMS zircon U/Pb geochronology. Of these, 27 samples (eight with U/Pb ages) are from two NE-SW trending near-horizontal drillholes (1100 and 1200 m long) that transect most of the pluton. Harker-type diagrams show apparent fractional crystallization trends, with SiO$_2$ and MgO ranging from 53-65 wt. % and 1-3 wt. % respectively. Samples with high SiO$_2$ or low MgO, have low CaO, FeO, TiO$_2$ and P$_2$O$_5$ and high K$_2$O. However, when composition is plotted against U/Pb ages, the oldest samples are more felsic and the youngest samples are more mafic. The younger samples also have high Sc, V, Ni and Cr. These trends are opposite to those expected for single batch fractional crystallization. The geochemical trends can be explained by blending an original intermediate composition magma with increasing proportions of recharging mafic magma. Structural relationships in the country rocks and numerous internal gradational contacts indicate the pluton passively inflated near the surface into space created by floor subsidence as fault bounded blocks of upturned strata sank into a mid-crustal magma chamber.

Geochemistry and ore-forming processes of multistage granitic magmatism in the Central Iberian Zone: Segura-Panasqueira Belt (Portugal) case study

Ivo Martins, António Mateus, Isabel Ribeiro da Costa, Miguel Gaspar, Icaro Dias da Silva
Departamento de Geologia & Instituto Dom Luiz (IDL), Faculdade de Ciências, Univ. de Lisboa, Portugal

Granite-related ore deposits are major resources of many critical metals and have been one of the major targets of mineral exploration over the last decades. The Segura-Panasqueira Belt, located in the Central Iberian Zone (ZCI), is one of the several well-defined belts that form a Sn-W-Li world-class province of Paleozoic age in the Iberian Variscides, comprising several long-lived granite-related ore systems. Despite the growing interest in these ore systems, several aspects remain poorly understood. Our ongoing work aims to understand the processes controlling the different degrees of differentiation and metal enrichment during the generation of silicate melts, using some examples from the Segura-Panasqueira belt as case studies. For that purpose, a comprehensive multi-elemental whole-rock geochemical characterization of the main (composite) plutons within the belt was conducted, representing the two major regional magmatic pulses: Cambrian-Ordovician and Carboniferous-Permian (Variscan). Preliminary results show that: (i) the majority of Cambrian-Ordovician tonalites and granodiorites are weakly peraluminous I-type, calcic to calc-alkaline and magnesium rocks; (ii) the Carboniferous-Permian monzogranites and granites are highly peraluminous S-type, calc-alkaline to alkali-calcic and magnesian to ferroan rocks; and (iii) the Variscan magmatism is clearly more fertile, especially the strongly differentiated and ferroan leucogranites from the Penamacor-Monsanto and Segura plutons, which were generated by high-T partial melting of pelitic rocks.

The granitic facies of the Penamacor-Monsanto and Segura plutons are characterized by degrees of differentiation (Rb/Sr up to 18.93 and 14.53, respectively) and metal enrichment (up to 391 and 48 ppm Sn, 661 and 305 ppm Li, 27.3 and 32.7 ppm Nb, 8.83 and 10.5 ppm Ta, respectively) close to granitic rocks related to ore-forming processes at reference places such as Panasqueira (W-Sn) and Argemela (Sn-Li).
New insights into the Neoarchean geological evolution of the Yilgarn Craton and implications for gold explorers

Quentin Masurel, Nicolas Thébaud
Centre for Exploration Targeting, The University of Western Australia, Crawley, Western Australia, Australia

Neoarchean rock successions worldwide not only provide invaluable insights into the geological processes at play during the Early Earth history but also host world-class mineral systems including gold and nickel. The discussion on the origin of Neoarchean greenstone belts, however, remains polarized between views advocating subduction-accretion processes and non-uniformitarian models advocating plume-crust interaction. Much of this debate focuses on the interpretation of geochemical proxies. Yet, our ability to understand the geological evolution of Archean cratons is fundamentally dependent on stratigraphic reconstructions across greenstone belts.

The Yilgarn Craton in Western Australia is one of the key pieces of Archean crust on Earth and is extraordinarily well-endowed in gold and nickel. In this study, we re-examine and compare the stratigraphic record of key regions of the Yilgarn Craton in order to propose a coherent and testable tectonic scenario for its Neoarchean geological evolution. We show that the distribution of basement fragments across the Kalgoorlie Terrane questions the validity of the historically proposed arc terrane accretion model and terrane boundaries. Our revised stratigraphic scenario supports a para-autochthonous model whereby crust from a proto-Yilgarn continental mass was extended and thinned, ultimately resulting in the eruption of the Kalgoorlie Large Igneous Province between ca. 2720 and 2690 Ma along the Youanmi-Burtville paleo-craton margin. Inversion of this intracontinental rift during the ca. 2680-2630 Ma Yilgarn Orogeny led to final assembly of the Yilgarn Craton as recognized today.

In terms of architectural controls on gold systems, a direct exploration targeting implication that can be derived from this para-autochthonous model is that zones of high fluid flux and mantle-derived magma bloom occurred along rift zones wrapping around older, long-lived, reworked crustal blocks. Thus, exploration efforts should focus on identifying the crustal architecture of this intracontinental rift across scales (regional, camp, deposit).
Metal distribution in the gossans of Lagoa Salgada, Caveira, Lousal, Montinho, Aljustrel, São Domingos and Chança VMS deposits, Iberian Pyrite Belt, Portugal

João X. Matos, Maria J. Batista, Teresa P. Silva, Daniel P.S. de Oliveira
Laboratório Nacional de Energia e Geologia, Aljustrel, Portugal,

Jorge M.R.S. Relvas, Fernando J.A.S. Barriga
Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

The Iberian Pyrite Belt (IPB) metallogenetic province includes ca. 100 massive sulfide+stockwork deposits distributed over Alentejo/Portugal and Andalusia/Spain, hosted by felsic volcanic rocks, black shales and cherts of Late Famennian to Tourmaisian age, which form the Volcano-Sedimentary Complex (VSC). VSC exhumation since the Paleogene is reflected by near surface deposits’ total/partial oxidation forming gossan structures (up to 50 m thick) developed on top of ore lenses and stockworks. Chemical, PIMA II SWIR and XRD data of the IPB Portuguese gossans were correlated: Lagoa Salgada, Caveira, Lousal, Montinho, Aljustrel, S. Domingos, Chança and Serra Branca. Lagoa Salgada present a complete gossan profile from base to top: primary massive/stockwork mineralization, supergene enrichment zone, massive gossan, earthy gossan, gossan deposits (infill breccia and coluvial deposits) and a paleosoil covered by Cenozoic sediments. Gossan metal enrichment occurs especially for Au, Ag, Pb, Sn and Cu, but also for Sb, V, P, Ba, Mo, Bi and Se. Gossan developed over stockwork mineralization presents minor metal content and earthy facies. IPB gossans, mined since Roman times, still preserve significant economic value. In Portugal, gossan metal resources are indicated at Lagoa Salgada (1.6 Mt) and Gavião complete profiles, Algares (0.36 Mt, incomplete profile) and mine waste with gossan fragments (ca. 4 Mt in São Domingos and unknown resources at Algares/Aljustrel). Kaolinite/halloysite supergene clay alteration related with deposit erosion occurs at Lagoa Salgada, Lousal, Caveira, Aljustrel and São Domingos. It decreases with depth and distance to the massive sulfide orebodies. In fault zones, jarosite, alunite, gypsum/anhydrite and barite veins occur. The occurrences of Al-bearing sulfates are consistent with circulation of very acidic and oxidizing fluids, at low temperature conditions, under both syn/late-Variscan and Alpine tectonic regimes. Gossan characterization is critical to mineral exploration, especially when significant enrichment zones occur.
Revelations through micro-characterization of komatiite-associated invisible Au

Helen B. McFarlane, Siyu Hu, Belinda Godel, Mark Pearce
CSIRO, Mineral Resources, Kensington, Western Australia, Australia

Allison Dugdale, Jack Clifford
Curtin University, Perth, Western Australia, Australia

Located on the richly gold endowed northwest margin of the Archean Plutonic Well Greenstone Belt of the Marymia Inlier, Western Australia, the Trident gold deposit (410 koz @ 8 g/t Au) provides a unique opportunity to investigate quartz-poor gold ores in an orogenic setting. Host rocks include intensely sheared, amphibolite facies, komatiitic ultramafic rocks in the footwall of an overthrust granite, previously likened to the “brown lodes” of the nearby Plutonic Au deposit. We demonstrate a novel multi-scale, multi-disciplinary analytical approach to better understand the structural and hydrothermal controls of Au mineralization. Elemental high-definition µXRF Maia maps of drill core from high-grade intercepts (>100 g/t Au) show coincident distribution of Bi and Au within veinlets parallel to an early tectonic foliation (S1) defined by high-strain, banded amphibole (Mg-actinolite)-chlorite±biotite assemblages. SEM images show native Au, native Bi and bismuth telluride occur along grain boundaries, cleavage planes and as inclusions in S1-parallel Mg-actinolite. This foliation is overprinted by biotite-(±Au±molybdenite)-rich shear planes attributed to subsequent potassic alteration and rheologically-controlled low angle thrusting and isoclinal folding measured in drill core. Polymetallic Au-Bi-Bi2Te3-MoS2 assemblages are noted along micro-scale rheological contrasts between banded phases, with molybdenite-free metal accumulation noted in fold hinges of overprinting upright F3 folds. X-ray computer tomography scans reveal the 3D distribution of Bi and Bi-Te veins, highlighting refolding and shearing during D2, and elevated density of gold particles in F3 fold hinges. This suggests D3 metamorphic conditions fell above the Au-Bi melt eutectic, facilitating remobilization and reprecipitation in dilatant zones. Our novel, scale-integrated approach illustrates the strong spatial association and structural control of bismuth and bismuth tellurides on the distribution of invisible gold in the intensely sheared ultramafic rocks, highlighting the complex relationship between polyphase ductile deformation, metamorphism and co-existing hydrothermal fluids and Au-Bi melt resulting in the transport and precipitation of gold.
Gravity recovery of gold – past, present and future

Teresa McGrath
Gold Technology, Group, WA School of Mines
Minerals, Energy and Chemical Engineering, Curtin University, Perth, Western Australia

The history and complexity of gold ore processing is directly tied to the unique physical properties of gold as well as its distribution within an ore body and its association with gangue throughout a deposit. Gold can occur as metallic gold (free) particles, easily recoverable by gravity methods until it becomes too fine. Gold can also occur locked in a sulfide matrix or in a mineral form, yielding varying degrees of refractoriness. Furthermore, gold can occur in all these forms in a single deposit.

Prior to cyanidation, gold production was mostly the result of concentration via gravity/density separation techniques. The known and recovered gold was the gold we could visibly see; coarse, free gold. While historical techniques such as jigging and sluicing practiced hundreds of years ago were sufficient for capturing gold from alluvial deposits, these types of deposits do not represent most ores being processed through a modern gold plant.

Today, deposits containing fine free gold, ~20 µm and smaller particles, are often being treated with high G-force batch centrifugal concentrators, such as Knelsons and Falcons, which can recover fine gold particles into a small mass (low mass pull), “high” grade, concentrate. However, low G devices like spirals and jigs, can still be found on some gold plants. These concentrators typically aim to recover gold contained within a sulfide mineral, with concentrates characterized by having a higher mass pull and lower grade, often requiring subsequent treatment prior to intensive cyanidation.

Understanding historical and modern-day gravity recovery methods as well as the importance of sampling, mineralogy, ore characterization, benchmarking and modeling validates their continued use in modern gold plants for gold recovery from amenable ores, and even highlights the potential application of gravity separation for gangue rejection with the intent of turning low-grade, uneconomic resources into reserves.

Compositional MAF and geostatistical analysis of geochemical data to reveal geochemical anomalies for natural resource estimation

Jennifer M. McKinley1, Ute Mueller2, Eric Grunsky3,4, Ray Scanlon4, Mark Cooper5
1Geography, School of Natural and Built Environment, Queen’s University Belfast, United Kingdom
2School of Science, Edith Cowan University, Perth, Western Australia, Australia
3Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Canada
4Geological Survey Ireland, Beggars Bush, Haddington Road, Dublin, Ireland
5Geological Survey of Northern Ireland, Dundonald House, Belfast, United Kingdom

Digital spatial data are becoming increasingly available for environmental studies through sub-continental scale and regional scale ground-based geochemical surveys and an ongoing global geochemical baseline survey. National surveys funded by major government and European investment to gather geochemical data across the Island of Ireland include the Tellus Project (a Department of Environment (DfE)-funded program) for Northern Ireland (NI), Tellus Border (EU INTERREG IVA-funded a joint program between NI and Republic of Ireland (RoI)) and the current Tellus Programme (a RoI national program). These data can be used to reveal geochemical anomalies for natural resource estimation. However, data sets such as geochemical survey data pose many challenges for exploratory data analysis and any subsequent geostatistical analysis. Geochemical data are compositional in nature in that they convey relative information. As a result, compositional data analysis (CoDA) methods are frequently used to extract information from geochemical data by treating log ratio or equivalently transformed data instead of analyzing the raw constant sum values. Using the Tellus soil geochemical database for the Island of Ireland, this study investigates compositional multivariate techniques including minimum/maximum autocorrelation factor (MAF) analysis that uses the spatial relationships of the data to determine the relative influence of mineral prospectivity anomalies on the geochemistry signature. Using the classification based on MAF analysis, the dominant MAF factors are explored in the framework of factorial kriging.
Manganese-based vectoring in distal carbonate replacement deposits

Peter K.M. Megaw, Lyle D. Hansen, Lex Lambeck, James A. McGlasson, Collin G. Jensen
MAG Silver Corp., Vancouver, British Columbia, Canada

Manganese is virtually ubiquitous in the distal zones of Skarn-Carbonate Replacement Deposits (CRDs) and provides inexpensive direct and indirect exploration vectoring guides to sulfide mineralization. The most obvious is Argentiferous Manganese Oxide Mineralization (AMOM); visually distinctive, pink to black, silver-bearing manganese-oxides deposited in carbonate and other wallrocks distal to sulfides. Visually less obvious, at least in daylight, are manganese-bearing “fugitive calcite” veins that commonly mark “feeder” and “bleeder” structures within, surrounding and extending outwards from skarn and sulfide replacement zones.

AMOM ranges from fracture coatings and fillings to fracture-controlled, three-dimensionally penetrating dendritic infusions. Although commonly modified by weathering, AMOM retains boxwork textures and geochemical and isotopic signatures indicating a primary origin from residual/distal ore fluids. Broadly, AMOM can provide an easily mapped and sampled, multielement geochemical halo outlining the overall limits of a subject CRD system. Importantly, distal AMOM generating fluids follow many of the same permeability controls as primary mineralization and therefore can be used to map and broadly understand these controls and potentially vector directly towards ore.

Fugitive calcite derives from host rock calcite dissolved during the coupled carbonate dissolution - sulfide precipitation replacement process. Carried away in the residual ore fluids, this calcite remains in solution until being redeposited as distal fracture and pore fillings. Trace quantities of manganese and lead are incorporated into the crystal lattice of fugitive calcite and induce a distinctive fluorescence color spectrum from gaudy orange to deep red under shortwave ultraviolet light. Lamping outcrops and core readily and inexpensively reveals the fugitive calcite veinlet network and paragenesis. Combined with UV color, this can illuminate the dominant structural controls on fluid escape pathways and potential vectors towards mineralization. Fluorescence color differences can also help guide consistent veinlet-based selective sampling for detailed, district-scale geochemical and carbon/oxygen isotopic halo definition and vectoring programs.
Subvolcanic P-T phase equilibria of H$_2$O-CO$_2$-fluid saturated, Be-U-Li-F-enriched topaz rhyolite from Spor Mountain, Utah

Celestine N. Mercer, Albert H. Hofstra
U.S. Geological Survey, Denver, USA

The Be-U-Li-F-enriched topaz rhyolite tuff of the Miocene Spor Mountain Formation, Utah hosts the Earth’s largest Be deposit and a small U deposit. Small F deposits occur in underlying carbonate rocks. Beryllium is essential for aerospace, defence, computer, medical and telecom applications. In 2015, Spor Mountain produced ~90% of the world’s beryllium with a ~70-year supply remaining. Thus, it is an important location to investigate the magmatic and hydrothermal processes of Be, U, Li and F enrichment.

Experimental petrology is a powerful tool to isolate fundamental variables and recreate conditions of ore deposit formation within the Earth. Equilibrium melting relations of a topaz rhyolite vitrophyre from Spor Mountain were experimentally determined to constrain pre-eruptive H$_2$O contents of topaz rhyolite magmas as a function of temperature. Cold-seal experiments were conducted at 200, 100 and 50 MPa (~7-1.5 km depth), 485-975°C, $f_{\text{O}_2}$~QFM-NNO+0.3, and a variety of fluid concentrations and compositions. Experimental results contain a wealth of information yet to be synthesized.

We have recast results from 114 experiments into pressure-temperature phase diagrams to create a framework for interpreting geochemical and thermobarometric information from Spor Mountain melt inclusions. The P-T phase diagram for melts saturated with a mixed H$_2$O-CO$_2$ fluid ($X_{\text{H}_2\text{O}}^{\text{fluid}}$~0.5, $X_{\text{CO}_2}^{\text{fluid}}$~0.5) agrees well with quartz stability defined by quartz-hosted melt inclusion thermobarometry. The presence of a CO$_2$-rich aqueous fluid may have been important in encouraging lithophile element retention in the silicate melt throughout decompression-induced degassing in the presence of chlorine; thus preserving lithophile elements in erupted volcanic glasses for post-eruptive hydrothermal enrichment. Upcoming micro-FTIR analyses of melt inclusions will clarify pre-eruptive CO$_2$ contents to test whether these topaz rhyolite melts were particularly CO$_2$-enriched and why.
Quantitative image textural analysis for copper flotation recovery
Javier Merrill-Cifuentes, Matthew J. Cracknell, Angela Escolme
ARC Research Hub for Transforming the Mining Value Chain and CODES, University of Tasmania, Australia

A key aim of geometallurgy studies is to improve predictions of rock behaviour throughout the mining value chain by better understanding relationships between rock properties and mineral processing response. With the current industry trend of diminishing grades and the increased mineralogical complexity of ore bodies, this type of information has become critical for the accurate estimation of value in a mining project. Furthermore, geometallurgical modeling can also provide important information for decision-making and process optimisation. In particular, flotation process quality is strongly affected by the spatial attributes of minerals such as ore mineral grain size distribution and their spatial association to gangue. These textural features affect the entrainment of undesired minerals into concentrate and affect the recovery of the valuable minerals by different mechanisms.

In this study, the improvement in the prediction of copper flotation recovery when using textural features was assessed in a dataset belonging to a porphyry Cu deposit in northern Chile. To account for texture, a feature extraction method named Mineral Co-Occurrence Probability Fields (MCOPF) was applied to a dataset of VNIR-SWIR hyperspectral imaging (500 μm pixel size) of the same drill cores from which the flotation samples were taken from. The MCOPF method provided a means to assess and identify textural and mineralogical traits that can be further linked to the mineral processing behaviour of certain geological units. As a result, a repeatable and robust way of incorporating texture into the geometallurgical workflows of an operating mine is proposed, generating new value from the emerging imaging tools for rock characterization that are commercially available.

Using scheelite composition and statistical analysis to distinguish ore deposits
Ana Carolina R. Miranda, Georges Beaudoin, Bertrand Rottier
Département de Géologie et Génie Géologique, Université Laval, Québec, Canada
Centre de Recherche sur la Géologie et l’Ingénierie des Ressources Minérales (E4m), Québec, Canada

Scheelite trace element composition records the physical and chemical characteristics of the mineralizing fluids. Given that scheelite can form in many deposit types, the relative abundance of some elements allows identifying different types of mineralization. Minor- and trace-element compositions of scheelite from different deposit types were acquired by LA-ICP-MS. Our results, combined with literature data, were investigated using partial least squares-discriminant analysis (PLS-DA) and Random Forest (RF) algorithm to investigate the potential of scheelite composition to predict deposit types. The PLS-DA results show that scheelite from orogenic gold deposits can be clearly distinguished from those from magmatic-hydrothermal deposits due to higher Sr, Ba and Pb, and lower Mo, Ta and Nb concentrations. Nevertheless, scheelite from different types of magmatic-hydrothermal deposits (i.e. skarn, porphyry Mo-W, greisen Sn-W and RIRGS) have close chemical compositions. Scheelite from RIRGS is chemically similar to those from reduced skarns, which may reflect similar magmatic contributions and the reduced nature of the mineralizing fluids. Although there is a small overlap, scheelite from oxidized skarn deposits can be discriminated from the remaining deposits due to their higher concentrations of Mo and As. Unlike PLS-DA, RF allows for accurate prediction of the scheelite provenance. Using Na, Mg, Mn, Sr, Y, REE, Pb and Eu anomaly as predictors, RF yields an overall prediction accuracy of 95%, with 88% of RIRGS, 99% of orogenic gold, 90% of oxidized skarns, 100% of porphyry Mo-W, 95% of reduced skarns and 94% of quartz-veins/greisen of the test data. Random Forest model results suggest that scheelite trace element composition can be used as an efficient tool for deposit type discrimination and source provenance prediction. Therefore, our results support the use of an RF classification model of scheelite composition to be applied as a predictive modeling tool in greenfield terrains by providing an accurate indication of deposit type.
Carbonatites host the main REE deposits, with bastnaesite being the main REE-bearing mineral of interest. However, bastnaesite mineralization processes are still debated, since both hydrothermal and magmatic processes affected most deposits. This study aims to experimentally assess if bastnaesite can be of magmatic origin, as well as the REE sink during carbonatite crystalliation. Crystallization experiments have been performed from 900 to 600°C at 1 kbar, on a REE-rich calcioarbonatitic composition. Calcite (Ca,REE)CO$_3$ is the dominant crystallizing mineral. Thus, the residual melt evolves toward natrocarbonatitic compositions as crystallization proceeds. Fluorine, Cl and water decrease the temperature of calcite saturation, allowing the system to crystallize at lower temperatures. REE are slightly incompatible with calcite, especially at low temperatures. Thus, the residual carbonate melt is slightly enriched in REE as crystallization proceeds. A small amount of britholite (REE,Ca)$_8$((Si,P)O$_4$)$_3$(OH,F) is observed at high temperatures and replaced by phlogopite KMg$_3$(AlSi$_2$O$_{10}$)(OH)$_2$ and apatite (Ca,REE)$_5$(PO$_4$)$_3$(F,OH) under 650°C. A small amount of pyrochlore (Ca,Na,REE)$_2$Nb$_2$O$_6$(OH,F) is observed under 700°C. However, no bastnaesite is found in any crystallisation experiments. We thus performed a bastnaesite saturation experiment at 600°C. The bastnaesite-saturated melt contains 20 wt% of REE: such a high value implies that magmatic saturation of bastnaesite is unlikely to happen in nature. Textural evidence implies the presence of a Na,Cl,REE-rich fluid at high temperatures and under hydrous conditions. As our results suggest that bastnaesite mineralization is unlikely to be magmatic and REE-rich fluids are observed in the system, fluids are probably the main mineralizing agent for bastnaesite.
Determination of the processes behind Sb, As and W enrichment in magmas using geochemical databases
Valentin Mollé, Giada Iacono-Marziano, Héctor Campos Rodriguez
ISTO, UMR7327, Université d’Orléans, CNRS, BRGM, Orléans, France

Eric Gloaguen, Johann Tuduri, Anthony Pochon
BRGM, Orléans, France

Magmatic heat sources allow hydrothermal fluids to transport and deposit various types of metals and metalloids. Antimony (Sb) is frequently spatially associated with mafic intrusions and may be associated with various amounts of other elements, such as arsenic (As) and tungsten (W). However, source-sink relationships in those settings remain poorly constrained. Whether mafic magmas contribute fluids, metals and metalloids to hydrothermal systems at the origin of Sb mineralization remains uncertain.

We investigated the Sb, As and W contents of magmatic rocks available in the literature, to assess mafic magmas as a potential source for metals and metalloids. Antimony, As and W are highly covariant, suggesting a common behaviour during magmatic processes. Their concentrations in oceanic magmatic rocks increase with increasing K2O content: up to two orders of magnitude in mafic compositions, and one order of magnitude through intermediate and differentiated compositions. Thus, differentiated alkaline magmas yield higher concentrations of Sb, As and W. Their variations with major and trace elements suggest a major role of mantle source processes, and a minor contribution from fractional crystallization. In particular, their concentrations in basaltic compositions show a good correlation with the La/Sm ratio, and an absence of correlation with the 87Sr/86Sr and the 143Nd/144Nd isotopic ratios, suggesting a crucial control of partial melting processes.

Continental magmatic rocks show a strong Sb, As and W variability, with values up to 3 orders of magnitude higher than oceanic rocks, suggesting crustal contamination. Post-magmatic alteration does not seem to have any effect on Sb, As and W concentrations.

We finally investigate mafic rocks spatially and temporally associated with Sb-Hg ± As-W-Au-Ag ore deposits and discuss the possible processes at the origin of their enrichment.
What does the geochronology of supergene alteration and Cu-enrichment tell us about the landscape evolution in the Atacama Desert?

Jorge Morales-Leal, Eduardo Campos, Rodrigo Riquelme, Jonathan Salazar
Departamento de Ciencias Geológicas, Universidad Católica del Norte, Antofagasta, Chile

Richard Spikings
Department of Earth Science, University of Geneva, Geneva, Switzerland

Supergene alteration (SA) and supergene copper mineralization (SCM) require climatic conditions that provide sufficient amounts of water for the leaching of sulfides exposed to surficial oxidized conditions, but not quantities of water that could promote erosion of the SCM. Thus, the SCM is the product of a delicate balance between uplift, denudation, and climate, factors that strongly control the geomorphology in the Atacama Desert. Geochronology of supergene minerals allows us to understand the period of SA activity, but they also can indicate changes in the landscape evolution that were critical for the development of the SCM along the Atacama Desert. We have collated 148 radiometric ages from previously published studies conducted between southern Peru and the southern segment of the desert in Chile (16° - 27° lat. S). New alunite and jarosite Ar/Ar ages from the southern high Precordillera (over 3000 m.a.s.l.) are also reported. The results of this compendium confirm how uplift and unroofing affect the conservation of the ages, and the influence of the climate for the ending of the SA and SCM along the Atacama Desert. The current hyperarid core of the desert is well-correlated with the stable period during the late Oligocene to middle Miocene that also facilitated the development of pediplains in the area. On the other hand, the northern and southern margins segments experienced different conditions, with ages notably younger, implying that the supergene processes are still active. Also, our radiometric ages reveal supergene alteration as old as ~42 Ma and young as ~3.5 Ma, which would confirm that the SA above 3000 m.a.s.l. in the Precordillera has different triggering factors than the supergene enrichment that was developed and conserved in the hyperarid core of the Atacama Desert.
Hypogenic mineralizations of W and Sn in Northern and Central Portugal, and Castille and León regions of Spain

Alexandra Mota, Fernando Noronha
Faculdade de Ciências da Universidade do Porto, Instituto Ciência da Terra – Pólo Porto-Portugal

Óscar Fádon
Salamanca Universidad, Salamanca, Spain

The main goal of this work was to frame the Variscan granites associated with Sn-W mineralization into a “Metallogenic Map”. For this purpose, a geochemical comparative study between Variscan granites located inside the “Sn-W Iberian Metallogenic Province” was carried out.

The Sn and Sn(W) deposits are mostly associated with synorogenic granites of mesocrustal origin. The highest Sn contents (~74 ppm) occur associated with the most evolved granites which record late muscovitization processes. They are characterized by a wide range of K/Rb (19-195) and Rb (240-796 ppm), low Zr (<43 ppm) and low REE (<32.8 ppm). The REE normalized profiles display low fractionation of light REE (LREE) comparing to heavy REE (HREE), with (La/Yb)_N ratios ranging between 1.9 and 9. The negative Eu_N anomalies vary between 0.31 and 0.70.

The W deposits can occur associated with different periods of synorogenic and late- to post-orogenic basicrustal granite magmatism. The more evolved granites are characterized by K/Rb ranging between 84 and 91, high Rb (417-461 ppm), Y (21-45 ppm) and Nb (24-35 ppm), and low Zr (30-66 ppm), Ba (36-71 ppm) and Sr (14-15 ppm). They are relatively poor in REE (SREE: 61.2-82.6 ppm) and the REE normalized profile shows low fractionation of LREE in relation to HREE, with (La/Yb)_N ranging between 1.41 and 5.01. The negative Eu_N anomalies are very low (0.07 to 0.09).

Thus, based on this study, we were able to show that the application of geochemical data made it possible to discriminate different types of evolved granites (leucogranites) and their association with mineralization. The geochemistry of leucogranites can be used as a clue to differentiation processes and make it possible to identify Sn and W prospective areas.

Joining the geochemical rocks: mapping the potential of mine tailings and waste rock in Australia

Gavin M. Mudd
Environmental Engineering, RMIT University, Australia

Australia has long had a large and vibrant mining industry, leading to enormous quantities of mine tailings and waste rock at operating, abandoned and rehabilitated mines across most parts of the country. Mine wastes can lead to environmental risks such as acid and metalliferous drainage, surface water and groundwater impacts, erosion, biodiversity loss and loss of land use after mining. To date, however, there has never been a unified assessment of these wastes, especially considering the various environmental risks they present. Conversely, there has never been any mapping of such mine wastes to assess their potential for reprocessing to extract additional metals or minerals, especially the ‘critical minerals’ which are essential to modern technologies such as renewable energy, electric vehicles and energy storage batteries. Reprocessing of tailings can facilitate better rehabilitation outcomes (such as shifting tailings to a former pit rather than being left above ground) as well as reduce liabilities for governments, industry and communities alike. This presentation will cover the research work which is developing a national approach to this multi-faceted challenge. A national mapping of mine sites and their key features for mine waste has been completed, with each site also having production data compiled to quantify mine wastes (where data is available) and finally a conceptual approach has been developed to apply a geochemical model to each site based on mineral deposit type and typical geochemical models for various elements of economic interest (e.g. primary metals such as gold, copper and zinc, or critical metals such as tellurium, indium, germanium and cobalt). Overall, the paper is a unique national study which should provide a framework for other such studies around the world. The potential is great, but much remains to be done to realise this potential and achieve greater benefits from mine wastes.
The Massif 1 of the Bakwanga kimberlite field: facies and diamond potential (Kasai craton, D.R. Congo)

Philippe Mukonki, Chabu Mumba
University of Lubumbashi, Department of Geology, R.D. Congo

Jacques Batumike
Université Officielle de Bukavu, Département de Géologie, R.D. Congo

Pascal Mambwe
KU Leuven, Department of Earth and Environmental Sciences, Belgium

The kimberlitic massif I of Bakwanga is located at Mbuji-Mayi within the Congo-Kasai Craton in the central Democratic republic of the Congo. This craton consists of amphibolites, gabbro-noritic and gabbro-charnockitic complexes, granites, granulites, gneisses and a migmatitic complex. The diamond exploration and mining operation are mainly conducted within the crater facies of the kimberlite that is characterized by the presence of different types of breccias constituted by varying proportions of clasts from the kimberlite (65-75% vol.), dolostone, limestone, siltstone and sandstone from the Neoproterozoic Bushimay Supergroup (20-35% vol.), and gneiss from the craton (1-5% vol.), all supported in a sandy clay matrix. Petrographically, the kimberlite in the diatreme facies exhibits a porphyritic texture with phenocrysts of garnet, diopside, olivine, biotite and carbonate. The matrix contains large quantities of femic minerals such as ilmenite, goethite and hematite. Two main crater facies kimberlites are distinguished in the massif. The first presents as blue, green or greenish-red colors due to the abundance of chlorite and/or both goethite and hematite during the weathering of the host rock. This facies is typically of pyroclastic origin and was deposited during the volcanic event. It contains 1.14 to 2.38 carats of diamond per m³. The second facies is an epiclastic kimberlite comprising a resedimented volcaniclastic unit exposed within the crater and around the crater margin. It is diamond poor or barren, probably because the diamonds were transported and deposited in a distal placer, yet to be discovered. Further investigations are required to understand the diamond distribution within this massif to improve the exploration strategy within the craters and unknown placer deposit(s).

Deep time exploration

R. Dietmar Müller
EarthByte Group, School of Geosciences, The University of Sydney, NSW, Australia

Understanding the association between tectonic and geodynamic processes and the timing – and therefore the location – of the formation of major mineral deposits requires the linking of geological and geophysical observations to plate tectonic and geodynamic models. To associate the likelihood of resource formation with a particular subduction/ rift setting or geological terrain, we need to trace relevant data through geological time. The recent development of global topological plate models now allows us to start implementing spatio-temporal “deep time” mineral exploration, leading to the generation of new ideas and more accurate predictive exploration models. The Deep Time Exploration concept is built on 15 years of development of the open-source GPlates software, and its companion, the pyGPlates python library, a powerful tool for on-the-fly reconstruction and analysis of multidimensional data through time. The Deep Time Exploration infrastructure enables the analysis and visualization of vast amounts of multidimensional data through geological time. Regional and global geological and geophysical data sets can be aggregated, building large scale custom-tailored data collections for use in mineral exploration. Geodynamic simulations of the Earth’s mantle can be connected to map the passage of ore deposit provinces over different mantle domains through time, providing information about the temperature, or upwelling/downwelling speed and potential fertility of different mantle domains in a minerals context. Hyper-dimensional data in a plate tectonic framework can be analyzed using machine learning techniques, to discover hidden associations between the formation and preservation of particular deposits and the tectonic/geodynamic history from continent-wide to regional/local exploration scales. A prototype of a cloud-based data and software infrastructure is being integrated into the GPlates Portal (http://portal.gplates.org/), with the vision of enabling end-users to produce mineral deposit probability maps through time, based on alternative plate models and combinations of open-access and their own in-house data.
3D geophysical-geological modeling of the Needle Falls Shear Zone (Saskatchewan, Canada): structural/tectonic controls on base metal mineralization

Espoir M. Murhula1,2, Irvine R. Annesley1,3
1ENSG, Université de Lorraine, France
2Université Officielle de Bukavu, DR Congo
3University of Saskatchewan, Canada

The Needle Falls shear zone (NFSZ) is a major crustal NE-striking discontinuity of the Paleoproterozoic Trans-Hudson orogen, marking the boundary between the Wollaston Domain to the west and the Peter Lake Domain and Wathaman Batholith to the east. The Paleoproterozoic metasedimentary sequence of the Wollaston Domain hosts Cu and Pb-Zn mineralization within a 30 km distance from the NFSZ. This proximity, as well as the coinciding age range for the onset of base metal mineralization and the ductile deformation, make it compelling to investigate their genetic relationship. For this purpose, gravity, magnetic and seismic reflection data are hereby combined, with bedrock geology. Outcropping up to 1.2 km across strike, geophysics suggests the NFSZ may be ca. 5 km wide, with a minimum depth of 2.2 s two-way travel time. Wider and shallower towards its northern end, this structure is thinner and deeper (at least 6 s TWT) at its southern end. In contact with the Wathaman Batholith, the NFSZ is steeply west-dipping but features complex dips in contact with the Peter Lake Domain. Copper occurrences seem located preferentially in low magnetic zones, making the latter exploration targets, whereas Zn-Pb mineralization shows no clear preference. Demagnetization throughout the shear zone, interpreted as a consistent transition of hydrothermal fluids and alteration, is revealed by magnetic data inversion, and dissolution is evidenced by low gravity zones on the potential field map. Therefore, the NFSZ most likely acted both as a conduit and barrier for mineralizing fluids in the eastern part of the Wollaston Domain, but the source for this mineralization in the whole mineral system requires further investigation. Seismic profile modeling indicates the presence of complex structural features and essential seismic patterns described elsewhere in crustal-scale shear zones. Finally, the Wollaston Lake Reflector, a seemingly sub-horizontal shear zone requires further study.
Textural and geochemical characterization of Bangombe and Bignomi manganese ore deposit in the francevillian series, Gabon: insights for better exploration and mining strategies

Alexis Ndongo, Norbert Ondo Zue Abaga, Mathieu Moussavou, Michel Mbina Mounguengui
Université des Sciences et Techniques de Masuku, Département de Géologie, Franceville, Gabon

Hele-Riin Juhkama, Kalle Kirsimae
University of Tartu, Department of Geology, Tartu, Estonia

Knowledge of the Fancevillian basin Mn deposits comes mainly from the study and mining of the Bangombe world class Mn ore, in which, the depositional context has been systematically extended basin wide. This study presents the description of three manganese profiles, two from the Bangombe plateau (sectors B7 and B17) and one from the Bignomomi plateau. In general, their mineralizing profiles include, from bottom to top, five distinct horizons consisting of massive ore (H1), platy ore (H2), transition layer (H3), pisolite (H4) and humic layer (H5). However, textural, geochemical and mineralogical analyses have highlighted several differences between the Bangombe and Bignomi profiles. The manganese enriched profile in the Bangombe deposit is on average two times thicker (11 to 12 m) than in that in Bignomi (3.5 to 5 m). Also, the ore-producing layer (platy horizon), is up to 5.5 m thick and more Mn enriched (up to 80.2%) in Bangombe plateau than in Bignomi plateau (0.8 m thick horizon with 37.5% of MnO). Moreover, the pisolites horizon in Bangombe (up to 7 m thick) is about three times thicker than in Bignomi (1.5 m thick), though the Mn content remains the same (15% Mn). These results, associated with the occurrence of gibbsite in the sandy clay gangue of platy ore deposit, and the Mn paragenesis of the mined layers (nsutite, pyrolusite, cryptomélane and lithiophorite), suggest intensive leaching under long and deep weathering in open and well-drained systems. Our findings suggest differential oxidation and leaching levels between the Bagombe and Bignomi Mn ore profiles and offer potential for developing better exploration and mining strategies.
Exploring the potential for critical metal resources in mine waste: geometallurgical characterization of cobalt-bearing minerals in tailings at the Capricorn Copper Mine, northwest Queensland

Loren Nicholls, Anita Parbhakar-Fox, Rick Valenta, Paul Gow
Sustainable Minerals Institute, University of Queensland, Brisbane, Australia

Helen Degeling, Vladimir Lisitsin
Department of Resources, Queensland Government, Brisbane, Australia

Rosemary Gray
29Metals, Capricorn Copper Mine, Gunpowder, Australia

Governments around the world are seeking to secure their supply of critical metals, with many investigating alternative sources such as mine waste to bolster resources. Cobalt is a critical metal that has applications in battery technology, superalloys and metallurgy, and its increasing demand is driven by the shift towards greener energy technologies. Cobalt is a by-product of major commodities (e.g. Cu, Ni) and there is opportunity for cobalt resources to accumulate in the waste streams of these mines. Given the significant risks tailings storage facilities pose, redefining wastes as a secondary resource is a sustainable approach to tailings management and securing cobalt supply. The Queensland Government’s New Economy Minerals Initiative (NEMI) is exploring the potential of critical metals, including cobalt, in key mine waste facilities chosen from the state’s extensive 15,000 abandoned and historical mine sites.

One such site is Capricorn Copper, an epigenetic, structurally-controlled copper deposit with associated cobalt. Over its long historical mine life, numerous waste storage facilities of varying ages and compositions have been established. Three field campaigns conducted over 2020-2021 included shallow pit sampling and two hand-augering programs completing 232.2 m in 26 holes down to 10 m depths. The first auger program returned assays up to 737 ppm Co in unoxidized tailings below 4 m, while preliminary pXRF results of the second program returned 1.5% Co at depths >6 m, with an average grade of 718.67 ppm Co. MLA and XRD results from the original shallow pits revealed cobalt is hosted in at least two phases; within pyrites and manganese-oxides, indicating variability in source material and cycling of cobalt between saturated and oxidized zones. Geometallurgical characterization of the tenor, mineralogy and liberation potential of cobalt-bearing phases will inform the prospectivity and economic viability of a cobalt resource and its recovery at Capricorn Copper Mine.
Size matters: why smaller soil particle sizes improve exploration geochemistry through cover

Ryan Noble, Anicia Henne, Fang Huang, Dave Cole, Morgan Williams, Tania Ibrahimi, Tenten Pinchand
CSIRO Mineral Resources, Kensington, Western Australia

The exploration soil sampling and analytical approach has not changed significantly over the past 30 years: that is, digest a dry-sieved, perhaps milled, soil sample and analyze the solution for elemental concentrations. Look at your key pathfinder elements, then rinse and repeat at the next tenement package. Industry needs to explore differently and that is the paradigm shift the CSIRO research team is driving by fundamentally changing the exploration soil analysis approach. In soils, the mobile element signature is commonly contained in the smallest particle size fractions, so the UltraFine™ workflow was developed to separate the <2 µm “ultrafine” soil fractions for multielement analysis along with other, commonly not used, physico-chemical parameters including spectral mineralogy, pH, EC and particle size distribution. This novel method increases concentrations of Au, Cu and Zn by 100-250% compared to results from the <250 µm fraction, and removes the nugget effect for Au. At multiple study sites across Australia and New Zealand, we demonstrate how the integration of elemental geochemistry of the clay size soil fraction with spectral mineralogy and other soil parameters can improve understanding of landscape processes and anomaly formation. In addition to improving the “standard” soil geochemistry, we have also incorporated machine learning approaches with spatial data to generate landscape types and integrate first pass geochemical interpretation into the basic laboratory output. In some examples, targets that were overlooked by standard methods are identified as coherent targets in settings like sand dunes and sheetwash areas in semi-arid landscapes that are notoriously difficult to explore. We will demonstrate these unsupervised machine learning techniques (e.g. dimensionality reduction and clustering) that enable rapid interpretation of survey datasets and accelerate the path to discovery.
Ni-PGE enrichment on the Vermelhos Cu deposit, Curaçá Valley district, Brazil
Tercio Nunes, Gema Olivo, Brian Joy
Queen’s University
Filipe Porto, John Thompson, Mike Richard, Pablo Mejia
Ero Copper Corp.

The Curaçá Valley, located in the Paleoproterozoic Itabuna-Salvador-Curaçá belt in the northern part of the São Francisco craton, Brazil, contains a significant number of Cu deposits. Ore zones are characterized mainly by chalcopyrite-bornite-rich lenses, massive ore, breccias and veins hosted in mafic-ultramafic rocks. Different genetic models have been proposed to explain the various styles of mineralization including magmatic sulfide and Iron Oxide Copper Gold (IOCG) models. The Vermelhos deposits, located in the northern region of the Curaçá district, comprise mineralized zones that locally exhibit higher Ni:Cu ratios than other deposits in the district. Ni-rich mineralization is hosted mostly in gabbro-norites and anorthosites containing magmatic orthopyroxene, clinopyroxene, plagioclase, phlogopite, +/-hornblende, chromite, apatite and monazite. The early sulfides include pentlandite, Ni-bearing pyrrhotite (0.1-1.4% Ni) and melonite (NiTe2) in sharp contact and/or filling embayments in magmatic phases. Chalcopyrite, various Ag-, Ni-, Bi-, Pb-, Pd- and Pt-bearing tellurides and electrum occur mantling, and in sharp contact with, actinolite. These sulfides are also associated with Cr-magnetite and ilmenite filling corroded zones in chromite and filling fractures in pyrrhotite that contain inclusions of phlogopite. Chlorite, K-mica, epidote, carbonate, serpentine, talc, pyrite and violarite overprinted the early phases. Based on the mineralogical and textural relationships and the fact that the sulfides occur with chromite-bearing mafic intrusive rocks, we propose that at least part of the sulfides (pentlandite and pyrrhotite) may have formed during late stages of magma crystallization associated with mixing of alkaline, mafic and primitive magmas (denoted by the coexistence of magmatic monazite, apatite, phlogopite and chromite). Mantle-derived magmas or crustal contamination may have provided the S for the magmatic sulfides. Chalcopyrite and the various precious metal tellurides may have been a product of late crystallization of sulfide melts and/or of hydrothermal processes at pressure and temperature conditions where actinolite and phlogopite are stable.
Global demand by the green energy transition for raw materials is likely to continue and is predicted to grow 5 to 10 times the current demand, due to increasing pressure from the EV sector within the next couple of decades. There is an increasing need to find new target areas especially for cobalt, which is used extensively within green industries. As cobalt is rarely a main commodity in an ore deposit it is challenging to create a single mineral prospectivity model for it. In this paper we describe a mineral prospectivity mapping study combining critical parameters derived from five different cobalt bearing mineral systems models within Northern Fennoscandian Shield, Finland: 1) Orthomagmatic Ni-Cu-Co sulfide deposits; 2) Outokumpu-type mantle peridotite associated volcanogenic massive sulfide (VMS) style Cu-Co-Zn-Ni-Ag-Au deposits; 3) Talvivaara black shale hosted Ni-Zn-Cu-Co-type deposits; 4) Kuusamo-type (orogenic gold with atypical metal association) Au-Co-U-LREE deposits; and 5) Iron-oxide-copper-gold (IOCG) Fe-Cu-Au-Co-U-REE-Ba-F deposits. Furthermore, a mineral prospectivity model combining geochemical anomalies derived from regional till geochemical surveys, bedrock drilling data and mineral indications from boulders and outcrops was integrated with mineral systems based mineral prospectivity models aiming to delineate favorable areas for cobalt exploration. We used the fuzzy logic overlay method in a GIS platform to combine datasets derived from publicly available regional-scale geological, geochemical and geophysical maps of the Geological Survey of Finland. Validation of the mineral prospectivity models were done with the ROC method using the exploration drilling data of known mineral deposits as validation sites. The resulting maps define new areas for exploration and the high-prospectivity areas coincide significantly with the current exploration license areas. It is expected that many of those areas will be tested. Separate models give distinctly higher ROC validation scores when compared to the integrated model indicating that the exploration drilling used for the validation was biased towards certain deposit types.
Resourcing a low emissions future through mineral discovery and responsible recovery

Sandra Occhipinti
CSIRO Mineral Resources, Perth, Western Australia, Australia

Resourcing a low emissions future through mineral discovery and responsible recovery is needed to mitigate the effects of climate change. As global energy demands rise, the majority of required growth will be met by renewable energy sources. Widespread electrification will result in increased demands for base and critical metals, with electrification and battery technology relying on increased supply of energy metals including lithium, cobalt, nickel and REE’s, some by up to 500%, testing the limits of metal supply. In order to meet this demand we need to build, translate and deploy newly created technologies rapidly across the exploration and mining value chain.

Metal discovery timeframes must be shortened, facilitated through effective exploration undercover and ore body characterization. This will be assisted by geophysical imaging and inversion combined with regolith geochemistry technologies. Effective and commercially available indicator or fertility minerals technologies will aid targeting, such as what is currently underway with the new Ultrafines+ fine fraction geochemical analysis tool. This analytical process targets particles less than 2 microns in size, such as clays and iron oxides which have more surface area to bind metals that move through the regolith, forming a geochemical signature of orebodies that may lie beneath them. Other regolith sampling methods, and understanding what parts of the regolith are best to sample for exploration geochemistry, are also important and can be tackled through combining sensor technologies with fundamental geoscience and landscape evolution studies. More precise geophysical inversion using multiphysics methodologies will enable better depth to the basement, or area of interest interpretation, helping with exploration targeting and drilling programs. Machine learning methods applied to geophysical datasets will be increasingly used to help understand the geology beneath cover, helping target exploration programs. Fast-tracked characterization tools for ‘on the fly decision support’ for field programs and providing more detail for geometallurgical studies will lower costs and risk, with these data fed across the value chain into solutions for mining that includes site- or commodity-tuned ore sorting and ore processing technologies.

A combination of ‘green metals’ production, hydrogen-based energy systems, partnered new systems for deep earth imaging, and autonomous sensor technologies, and digital decision-support tools will provide the step changes required to discover new resources and support sustainable and responsible mining operations. This, in addition to new ways of mining and processing, and possible on-site carbon abatement will help facilitate the resourcing of a low emissions future.
Uncovering what is where: metal deportment characterization of unconventional resources

Karin E. Olson Hoal, Nicholas Mitchell, Emily Liu, Eraklis Hristodoulou
Department of Earth & Atmospheric Sciences, Cornell University, Ithaca, New York, USA

Louisa Smieska
CHESS, Cornell High Energy Synchrotron Source, Cornell University, Ithaca, New York, USA

Hanna Horsch
SGS North America, Denver, Colorado, USA

Forward-looking metals climate-impact scenarios make assumptions based on present production data, past extraction methods, future demand estimates, and predicted environmental impacts. Each of these assumptions can be refined through better understanding of the geological materials needed in the future. The current mineral industry transformation is due in part to new applications and data analytics of micro-analytical methods applied to geomef frameworks, financial de-risking, process flexibility and ESG mitigation – yet these developments are not incorporated into future impact models. Rocks are inherently variable at the scale of critical element distributions such that deposits will be locally complex and mining operations will be responsive to the data drivers of mineralogical, textural and chemical variation.

For the coming focus on more complex geological materials, a more granular understanding of micro-mineralogical, geochemical and geological information will be necessary to uncover precisely what is where and how to get at it. Here, multi-method (synchrotron microxrf, Qemscan, LA ICPMS and scanning) workflows are used to identify the deportment of elements in materials not previously well characterized. CHESS’s X-LEAP initiative links metals from minerals to soils, organisms and the environment with oxidation state important to metal uptake. Seafloor geomet for the nascent Mn nodule industry ties finely laminated and potentially biogenic growth and collapse structures of metals (Ni, Cu, Fe and Mn) to mining and extraction process development. Mine waste characterization links mineral chemistry back to ores and in the process identifies how flowsheet changes (As, Zn) could lead to mitigated impact, while downhole mineral variability in low-T geothermal constrains porosity and permeability flow models. Integrating mineral characterization methods into geologically driven flowsheets should result in more precise, flexible and sustainable extraction methods with fewer impacts than current models predict.
Post-magmatic alteration of uranium mineralization in the Damara Orogen
Alex Otto
Deep Yellow Ltd

The southwestern Damara orogen in Namibia is host to 7% of worldwide uranium resources, placing Namibia in the top three of uranium producers. One of the region’s major types of mineralization is hosted by leucogranite intrusions, locally referred to as alaskites. The host terrane comprises Neoproterozoic sediments of the Khomas ocean basin. Following the collision of the Congo and Kalahari cratons, the Damara lithologies in the Central Zone were subject to granulite facies metamorphism peaking between 540 – 505 Ma. Following a protracted activity of felsic magmatism, uraniumiferous leucogranites intruded during the later stage of metamorphism at around 510 Ma. The leucogranites mineralogy is dominated by quartz, K-feldspar and albite, with minor biotite, magnetite, apatite, zircon and monazite. Primary magmatic uranium mineralization comprises uraninite, trace betafite and rare brannerite. Investigated samples from the Valencia, Rössing, Etango and Ongolo deposits show a variable degree of hydrothermal alteration of the primary magmatic mineralization. Magmatic uraninite, which contains thorium as a minor constituent, is replaced by the yellow uranyl silicates, uranophane and boldwoodite, and skeletal thorium minerals. The uranyl silicates also form thin cross-cutting veins. The hydrothermal fluids also affected betafite, which shows alteration along grain boundaries and fractures. Magmatic titanium-bearing biotite is replaced by chlorite and rutile. Detailed scanning electron microscopy permits the inference that the hydrothermal fluids were fluorine-rich, resulting in the formation of thorium-bearing silicates containing fluorine and rare earth elements within the former uraninite grains. The altered betafite shows a loss of uranium, rare earth elements and an addition of silicon. The occurrence of uranyl-silicates is linked to post-magmatic fluids by replacing uraninite and concentrating uranium into fractures. The fluid properties are thought to have been influenced by the replacement of magmatic biotite by chlorite thus releasing fluorine.

Cu-Ag-Pb mineralization of Agdim - Ait El Fersi sector, northeastern part of the Moroccan Anti Atlas belt: geological, mineralogical and geochemical characteristics
Lahcen Ousaid, Youssef Hahou, Khadija Diani, Zineb Aafir, Said Courba, Aziza Lamchaimech
LGEE Laboratory, Faculty of Sciences, Mohammed V- University Agdal, Rabat, Morocco
Rachid Ziyadi
Baraka Mining Company, Marrakech, Morocco

Polymetallic mineralization of the Agdim - Ait El Fersi sector is situated in the eastern Anti Atlas of Morocco. This area is located around 5 km from the west of Agdim N Ikhertan village, in the North-Eastern part of the Saghro inlier. Mineralization is hosted in late Neoproterozoic volcanic and volcaniclastic rocks, and in Lower Cambrian detrital sedimentary rocks. A network of faults has affected this area – they are oriented NW, E, NE and NNE. The NW to E and NE-trending structures have metallogenic significance because they are related to mineralized veins that contain Cu, Ag, Pb ± Hg, and Ba. Based on geological, structural and metallogenic characteristics, polymetallic mineralization of this area is linked to two major events. A late Pan-African event related to the extensional tectonic event of the late Neoproterozoic was responsible for the establishment of mineralization in the basement. It was followed by a late Hercynian-Atlasic event, which caused the remobilization of metals in NE-oriented structures. Geochemical analysis shows the polymetallic character of this mineralization, with high silver and mercury contents observed in some samples consistent with epithermal type mineralization. The geological context, as well as the mineralogical and textural characters of the Agdim - Ait El Fersi sector, are reminiscent of epithermal-type mineralization discovered at the nearby Imiter and Zgounder deposits.
The critical importance of ‘secondary prospectivity’ in a dynamic global climate

Anita Parbhakar-Fox

WH Bryan Mining and Geology Research Centre, Sustainable Minerals Institute, University of Queensland, Indooroopilly, Queensland, Australia

Mining has a critical role in providing essential mineral commodities for the transition to low emission energy generation, transmission and storage required to meet emission reduction targets and minimise global warming. However, there is increasing global focus on: i) Environmental, Social and Governance (ESG) risks in mining; ii) adoption of circular economy principles; and iii) waste reduction across all industries. Motivated by this, a new business opportunity to perform ‘secondary prospectivity’ analysis on mine waste is gaining momentum. In Europe, Chile, Canada, Australia and the United States alone, significant efforts by both Government organisations and the mining industry are underway to characterize and determine valorisation options for mine waste. For example, in Queensland, Australia reprocessing of tailings is being undertaken at the Century Mine (77.3 Mt @ 3.1% ZnEq), with plans to also recover Au at both Mt Morgan (10 Mt @ 1.1 g/Au) and Tick Hill (630,000 t @ 1.08 g/t Au) mines. Similarly, in Tasmania, Australia, remining tailings at the Hellyer mine (2.99 wt.% Pb, 2.35 wt.% Zn, 2.57 g/t Au and 92 g/t Ag) has been ongoing since the late 2010s. New activities to continue exploration in these ‘next-gen ore deposits’ are underway across Australia with significant funding from State and Federal Government agencies. Through this research, the identification of mine waste prospects with potential to supplement the increasing demand for critical metals (e.g. Co, REEs and In) is a focus. Early results indicate that IOCG and sediment-hosted wastes are prospective for Co; and greisen and VMS wastes for In. Looking ahead, an international ‘Mine Waste to Resource’ standard should be developed to enable new opportunities for economic rehabilitation to be identified by a range of stakeholders, therefore helping the global community de-risk existing and future mine wastes.
Opportunities for valorisation of spent heap leach materials- examples from Northwest Queensland, Australia

Anita Parbhakar-Fox, Laura Jackson
W.H. Bryan Mining & Geology Research Centre, Sustainable Minerals Institute, The University of Queensland, Australia

Helen Degeling
Department of Resources, GeoResources, Geological Survey of Queensland, Australia

Heap leaching is a well-established metallurgical technology which allows metal recovery (e.g. Au, Cu, U) from low-grade ores. However, spent heap leach materials remaining at abandoned or historic mine sites may represent a potential source of contamination. Across Queensland, heap leaching was employed as a technique to process Cu ore from oxides. At present, there is no defined methodology to rehabilitate these waste features therefore economic rehabilitation options (i.e. recovery of new economy minerals/metals) could be considered.

This study focused on geometallurgical characterization of three heap leach piles located at the Lady Annie mine, Mt Cuthbert Cu-operations and the abandoned Pindora Cu mine, Northwest Queensland. Sampling of materials was undertaken in 2020 with a combination of surface samples, salt samples precipitated around the pile edges and samples ~30 cm depth collected (n= 122). All samples were chemically analyzed by 4-acid digest with 30 samples selected for detailed mineralogical (XRD and MLA) evaluations. Mineral chemistry analysis (LA-ICPMS) was performed on several oxide, sulfate and sulfide minerals to determine deportment mode of select critical metals (i.e. Co and REEs).

At Lady Annie, quartz, gypsum, goethite and K-feldspar dominated the mineralogy. Cobalt ranged from 54 to 120 ppm and was goethite hosted. At Mt Cuthbert the mineralogy differed to Lady Annie with quartz, chlorite, biotite, plagioclase and jarosite dominating. Cobalt ranged from 23 to 805 ppm with the highest concentrations measured in the salts. Quartz and iron oxides dominated the heap leach mineralogy at Pindora. Assay results for Co ranged from 55 to 342 ppm with Co hosted in oxides. In contrast to the other sites, REE content was higher with Ce (average: ~200 ppm), La (average: ~123 ppm) and Nd (average: ~52 ppm) notable. Leach testwork is now being conducted to determine the recoverability of Co and REEs from these waste materials.
Characterizing the mineralogical and geochemical halo of the giant Mt Isa Pb-Zn-Ag-Cu deposit using integrated hyperspectral and X-ray fluorescence (XRF) core scanning technology

Ali Parchegani, Nathan Fox, Paul Gow, Rick Valenta
WH Bryan Mining and Geology Research Centre, Sustainable Minerals Institute, University of Queensland, Australia

As the trend continues toward exploration for deeper targets that are less well-defined in traditional exploration datasets, the importance of being able to recognize the subtle indications of a halo to a major mineralized system is increasing. Halos surrounding ore systems represent systematic variation in the chemical or mineralogical composition of the host rocks or specific alteration minerals with increasing distance from mineralization. Such halos may extend for hundreds or thousands of metres beyond the extent of economic mineralization but may be difficult to detect using standard characterization tools. The vectoring within halos is critical for exploration, particularly in deeper and more challenging environments. New tools are needed to detect subtle anomalies and vectors early in an exploration campaign, without the benefit of extensive pre-existing specific knowledge of the targeted orebody.

In this study, integrated core scanning technologies have been applied for the first time at Mt Isa to better define the mineralogical and chemical halo surrounding this world-class Zn-Pb-Ag-Cu deposit, located in northwest Queensland, Australia. Systematically spaced diamond drill cores located on a N-S oriented transect extending more than 10 km away from the Mt Isa ore body have been analyzed using hyperspectral imaging and linescan X-ray fluorescence (XRF) core scanning technologies. This high spatial resolution data records vertical and lateral changes in the chemistry and mineralogy of the Urquhart Shale, the host sedimentary sequence to ore at Mt Isa. Fine-grained pyrite is the most abundant sulfide at Mount Isa and forms a pyritic halo to the mineralized system that extends nearly 10 km along strike away from the currently exploited orebodies. This halo is also characterized by systematic changes in texture, mineralogy, mineral chemistry, and whole rock and trace element lithogeochemistry.
Critical metals in sulfides of the Tisová Cu (Fe-As) deposit (Bohemian Massif, Czech Republic): results from LA-ICPMS study

Jan Pašava, Irina Andronikova, František Veselovský, Anna Vymazalová, Ondřej Pour
Czech Geological Survey, Geologická 6, Praha 5, Czech Republic

The Tisová Fe-Cu-As-deposit is located in the Krušné hory Mts in the west part of the Bohemian Massif. The deposit has been mined intermittently since the end of the 12th century, with peak activities in the 15th - 17th and 18th centuries and with last mining occurring from 1959 to 1973. The deposit forms a number of concordant ore lenses concentrated in three horizons: lower, middle and upper, within a sequence of phyllitic metasediments, with interbedded metabasic layers, between the Karlovy Vary and the Smrčiny granite plutons. Several genetic models including sedimentary, volcanogenic (Besshi-type deposit), metamorphic and epigenetic/hydrothermal have been proposed. Main ore minerals are predominantly represented by chalcopyrite, pyrrhotite and three generations of pyrite (Py1, Pyl, PyII), generally accompanied by arsenopyrite, magnetite, sphalerite, marcasite, bismuth, bismuthinite, jamesonite, ullmannite, cobaltite, williamite, skutterudite and electrum. The distribution of critical metals (Co, In, Bi, Se, Ge and Ga) in selected major Fe, Cu and Zn sulfides were the focus of this study. Cobalt is present in all sulfides with the highest median value of 431 ppm in epigenetic/hydrothermal pyrite (Py1, n = 580). Indium is predominantly concentrated in sphalerite (median = 157 ppm, n = 69). Bismuth and selenium have the highest median values of 1340 ppm and 87 ppm, respectively, in marcasite (n = 10). The highest median value of Ge (2.7 ppm, n = 417) was found in chalcopyrite and its peak concentration (9.4 ppm) is bound to pyrrhotite (isomorphically). The highest galium median value (2.7 ppm) was detected in synmetamorphic pyrite (Py1) while its maximum content (36.8 ppm) was measured in chalcopyrite. We suggest that the chemistry of sulfides is in support of epigenetic-hydrothermal model and that the Tisová deposit can be considered a prosperous resource of CRM (especially Co).
Metamorphic evolution and metallogenetic value of the Tokmovo megablock and its tectonic position in the Volgo-Uralia segment, East European Craton

Tatiana A. Pavlova, Alexander V. Samsonov
Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM), RAS, Moscow

The Early Precambrian Volga-Uralia crustal segment represents the eastern part of the East European Craton. It is completely buried beneath a thick sedimentary cover and data on its structure and composition are based on previous geophysics and deep wells core research. The Tokmovo megablock is a western part of the segment. Gravity and magnetic geophysical data suggest it has a dome structure, typical for granite-greenstone terrains (GGT). The GGT nature of the Tokmovo block is also supported by core samples, which comprise three main types of rocks. Metabasites vary in composition and may represent relics of volcanic belts. Predominate Bt-Opx and Bt-Hbl plagiogneisses are regarded as metamorphosed tonalite-trondjemite-granodiorite (TTG) intrusions. U-Pb SHRIMP dating of zircon cores show that the TTG granitoids formed at 2.72-2.86 Ga. A metamorphic event (represented by zircon rims) dated at 2.7 to 2.6 Ga is the object of this research.

A one stage metamorphic evolution has been recorded in these rocks. Maximum values of the metamorphic thermodynamic parameters were identified in the Grt-Opx-Cpx-Hbl granofels within the cores of garnets and orthopyroxenes and correspond to middle-pressure granulite facies metamorphism (P 10-11 kbar, T = 720-810°C). Lowest values correspond to the amphibolite facies (5-7 kb, 680°C). The uniformity of garnets, absence of inclusions and of oscillatory zoning, a strong decrease in pressure against gradual decrease in temperature indicate one-stage metamorphism of the “Aldan” type – an uplift with cooling along the steep Archean geotherm.

The megablock is framed by Paleoproterozoic orogenic belts, which represent the collision zones. Such zones are characterized by their deep origin and long subsequent evolution, inherited heterogenetics related to Archean-Early Proterozoic accretionary processes and associated metallogenesis, e.g. the Aldan shield gold province in Siberia. Such gold occurrences may be revealed in the paleoorogen zones under the Phanerozoic cover.
The Santo Tomás project, Sinaloa and Chihuahua, México: a particularly elongated porphyry copper deposit

Jocelyn Pelletier¹, Miguel Quintana², Evelyn K. Caiza², Paul McGuigan²,³, William X. Chávez Jr.⁴

¹Oroco Resource Corporation and Geogenius Exploration Consulting
²Oroco Resource Corporation
³Cambria Geosciences Inc
⁴New Mexico School of Mines

Oroco Resource Corporation recently began exploring the porphyry Cu-Mo deposit at the Santo Tomás project, Sinaloa, México. A recent re-estimation of the historical mineral resource indicates 822 million tons with an average grade of 0.32% Cu. The 57.2 Ma Santo Tomás hydrothermal system is developed within Cretaceous-age carbonate rocks that overlie Jurassic-age andesite. Our work indicates that the deposit corresponds to a porphyry dyke complex that generally intruded along mylonitic shears; porphyritic monzonite intrusions can be followed at the surface for more than 4.5 km. In addition to porphyry-style mineralization, the Brasiles zone and the upper part of the Santo Tomás deposit hosts Zn-Pb-Fe-Ag-Au polymetallic skarn, Carbonate Replacement Deposit-style occurrences and Au-Ag specularite-mushketovite-quartz veins.

Santo Tomás differs from other porphyry Cu-Mo deposits by its extended intrusion-related length and dyke-like morphology, but mainly for the Cu-stockwork localized in the upper summit of the porphyry intrusion complex. Field geological observations indicate that a right-lateral component was active along local faults that controlled emplacement of the deposit. Due to this strong structural control, hydrothermal events are superposed along the same structures, reflected in the greatest Cu grades occurring along specific vein directions; mainly the A-veins forming breccia when overprinting the biotite-rich potassic alteration zones. Andesite and limestone host rocks have been altered and mineralized because they acted as lithologic-geochemical buffers for mineralization, creating stockwork zones with locally greater Cu grades. We surmise that this is attributable to structural porosity, resulting in wider veins, and reduced density of veins. A continued drilling program at the Santo Tomás suggests that this system offers the possibility of becoming one of the great copper deposits in México.
Orogenic-type gold deposits often preserve high-grade mineralization in quartz veins that concentrate significant gold in a small volume. Gold concentration is thought to be achieved through the accumulation of metals transported as dissolved species in hydrothermal fluids from their source to the ore deposit. The general low metal solubility in orogenic systems aqueous solutions needs to be compensated to explain economic mineralization. In the case of gold, increasing evidence suggests that nanoparticle suspensions nucleating proximal to the ore deposit are required for the formation of bonanza gold grades. However, as the source of gold is spatially disconnected from the deposit location, it is not known how the transport of gold nanoparticles is achieved. In this study, we collected gold-rich quartz vein samples from five locally high-grade orogenic gold deposits that formed at crustal depths ranging from 1.5 km to > 5 km below the surface. The gold mineralization formed in different host lithologies ranging in age from the Archean to the Cretaceous. We conducted a detailed petrographic investigation of the coarse gold samples by Transmission Electron Microscopy (TEM) that revealed the systematic occurrence of metal nanoparticles (electrum, silver oxide, gold and copper) preserved within amorphous silica and/or amorphous or micro-crystalline carbon as inclusions in gold or directly adjacent to gold grains. These new observations suggest that stabilisation of metal nanoparticles may be achieved through the Earth’s upper crust. We propose that metal nanoparticles are stabilized by colloidal silica. Our observation offers a step change in our understanding of metalliferous deposit formation.
The new epithermal gold deposits within the Okhotsk-Chukotka volcanic belt, north-east of Russia

Tatiana A. Pilitsyna (Pavlova)
Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM), RAS, Moscow

Alexey G. Pilitsyn
Institute of Mineralogy, Geochemistry and Crystal Chemistry of Rare Elements (IMGRE), Moscow

Alexander V. Volkov
Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry (IGEM), RAS, Moscow

The Okhotsk-Chukotka volcanic belt (OChVB) was formed in the North-East of Russia during the Meso-Cenozoic as an active continental margin, known for numerous gold-silver deposits. The OChVB is composed of calc-alkaline volcanic rocks and intrusions of similar age and composition to the volcanic rocks. Distinctive features of gold-silver mineralization in the OChVB for this period of formation of epithermal deposits in comparison with earlier epochs are:

1) the deposition of arsenopyrite precedes the deposition of polysulfide associations; 2) the presence of a wide range of antimony-arsenic silver sulfosalts in ores; 3) the gold-silver ratio fluctuates within significant limits - from 1/10 to 1/1200; and 4) a high selenium content of the ores.

Geochemical mapping within the OChVB identified geochemical zones associated with ore-forming processes of global rank by the multiplicative indicator Au*Ag*As. Within zones, the perspective areas Kypatap (with a contrasting anomaly of the Au*Ag*As indicator) and Televeyem were identified and studied during field work.

Kypatap reflects the association of the middle and upper ore erosional section. Mineralization occurs in highly altered felsic rocks. The Televeyem mineralization also occurs in felsic rocks. The closest analogs are Kupol, Sopka Rudnaya and Dvoinoe deposits.

The ores of both areas are characterized by: 1) structural position in the frame of a volcano-tectonic depression; 2) variable thickness of ore veins; 3) fine-grained nature of ore mineralization; 4) large range of gold fineness; 5) predominance of silver over gold; and 6) the presence of metasomatic zoning. However, Kypatap has gold-silver mineralization spatially associated with the formation of secondary quartzites and metasomatized feldspars and the main productive hypogenic mineral assemblages in the Televeyem are gold-pyrargyrite-polybasite-acanthite-adularia-quartz and gold-aguilarite-Se-acanthite-quartz. The report will present the ore characteristics, metasomatic zoning and their link with areal anomalies of various multiplicative indicators of local and global rank in the both areas.
Subaerial hot springs and near-surface hydrothermal mineral systems past and present, and possible extra-terrestrial analogues

Franco Pirajno
Centre for Exploration Targeting, The University of Western Australia, Crawley, Western Australia

The surface expression of shallow hydrothermal mineral systems are typically subaerial hot springs, fumaroles and geysers. Fumaroles and geysers usually occur in volcanic craters and in most cases, also occur in hot spring environments. Subaerial hot springs are characterized by siliceous- and carbonate-rich chemical sediments, such as sinters and travertines, respectively. Sinters are commonly enriched in various metalliferous elements (e.g. Au, Sb, As, Ag, Tl). Hot spring surface discharges are also characterized by pools, which exhibit bright colours due to the presence of microorganisms such as algae and pigmented bacteria in microbial mats. Present-day examples include the fumaroles and hot springs of the White Island volcano (New Zealand), the world-renowned Yellowstone caldera (USA) and the Afar region of the East African Rift System. The Afar triangle, in the northern part of East African Rift System, provides a good example of hot springs associated with evaporative deposits. The Tuli-Sabi-Lebombo triple junction rifts were formed during the ~180 Ma Karoo igneous event in southern Africa, of which the Tuli arm is the failed rift (aulacogen), as is the Afar region. The Tuli rift is effectively an unusual, if not unique, tectono-thermal setting, because it comprises Karoo-age hot springs systems and associated vein stockworks and breccias, which includes the Messina Cu deposit as well as currently active hot springs with sinter deposits probably due to post-Karoo uplift. Other examples include the fumarolic pipes, sinters and associated vein systems in the ignimbrites of the Erongo Volcano-Plutonic Complex in Namibia; and banded chert rocks in the Killara Formation of the Palaeoproterozoic Capricorn Orogen (Western Australia), interpreted as hot spring chemical sediments, which also show evidence of “fossil” microbial filaments. A brief overview of possible analogues of hot springs on planet Mars includes occurrences of opaline nodular silica in the Gusev Crater that are clearly indicative of fumarolic activity.
Geochemical zoning patterns in carbonate wallrocks of the Candelaria Cu-Au district, Chile

Stephen Piurkowsky, Zhaoshan Chang
Department of Geology and Geological Engineering, Colorado School of Mines, Golden, Colorado, USA

Paula Brunetto
Lundin Mining Chile SpA

In the Candelaria Cu-Au district, Chile, calcite-dominant veins occur in the Chañarcillo group calcareous rocks that are above ores and host some ores. They are the distal expressions of the mineralizing fluids. In this study, samples of the veins and the wall rock were collected along traverses that extend from known orebodies to barren rock up to 8.5 km away. The samples were analyzed for geochemistry, calcite trace elements (LA-ICP-MS), and C-O-Sr isotopes for distal signatures and trends.

Vein and wallrock geochemistry show Cu maximum (>1000 ppm) being closest to ore (<100 m), then Zn (>600 ppm), Pb (>100 ppm), and Mn maxima increasingly farther away. The Mn maximum (>10,000 ppm) occurs 1-3 km from ores; farther along faults. The Mn concentrations return to background (~1,300 ppm) at distances of ~5-6 km. Calcite composition shows similar trends, but without Zn and Pb. The Sr isotope composition of near-ore vein calcite is close to primitive a magmatic signature (~0.704) and it increases to be similar to that of the carbonate wallrocks (~0.707; open ocean carbonate signature) at ~4.5 km distance. Wallrock 87Sr/86Sr ratios decrease towards ores, likely due to the addition of hydrothermal calcite closer to ores. Oxygen isotope compositions of water in equilibrium with the vein calcite are higher (~13.0-2.5‰) near ores, due to contributions from magmatic and meteoric waters and dissolved wallrock carbonates. It decreases away from ores, down to ~10‰ at ~5 km, then remains at such values 5-8 km away from ores, indicating greater meteoric water component and less dissolved wallrock carbonate. The water C isotope signature is dominated by wallrock carbonates near ores (~1.4 to -2‰), and decreases away to -8 to -4‰ at ~5 km, then remains at such values at 5-8 km distances, probably due to less wallrock contribution and more organic components.

2D mineral predictive mapping with machine learning algorithms in Colombia

Luis Alberto Pizano
RWTH Aachen University

Andreas Barth
Beak Consultants GmbH

The combination of machine learning (ML) algorithms and GIS based approaches has allowed the development of new methods in mineral exploration. One such case is that of the integration of predictive modeling and mineral predictive mapping as a tool to support mineral deposit targeting. In this study, artificial neural networks (ANN), under a hybrid approach, were implemented in conjunction with the mineral systems method in order to identify the most suitable areas for selected mineral deposit types (porphyry, orogenic, epithermal and intrusion-related-Au deposits). This work is a novel application of this methodology in Colombia for a region of approximately 21,867 km² and aims to improve the knowledge of mineral deposits from the data in the hands of the Servicio Geológico Colombiano (SGC). The best performance was obtained for an ANN with a single hidden layer and for maximum number of iterations between 250 and 500. The overall performance and verification of the models was carried out through the examination of receiver operator (ROC) and mean square error (MSE) curves, with values over 0.9 and below 0.02, respectively. Validation of the same models was carried out using different ANN configurations as well as the available geochemical data. Target areas of interest were selected for future exploration campaigns in order to identify the respective mineralization indicators.
Improving precious metal detection in groundwater: a comparison of sorbents

Chloe Plet, Nathan Reid, Belinda Godel, Ryan Noble
CSIRO Mineral Resources

Groundwater anomalies form extended geochemical haloes that can be useful to target prospective mineral deposits. These haloes are widespread because of the mobile nature of groundwater. However, for precious metals (e.g. Au, Ag, Pt and Pd), these anomalies are often present at concentrations in the ng/L (ppt) range. While this is not an issue for fresh groundwaters, when water is more saline, such low concentrations are at the limits of analytical techniques. These limitations are an issue for countries like Australia, where groundwater is largely brackish to saline, and most of the land is blanketed by exotic cover. Therefore, over the last four decades, tools and approaches to overcome the issue of salinity when analyzing precious metals in groundwater have been developed. One such approach is the pre-concentration of precious metals onto adsorbing materials. However, limitations remain associated with the protocol and analytical practices.

To improve the measurement of these precious metals, we investigated the potential of three adsorbent materials – activated carbon grains, carbon fiber fabric and Purolite resin. To compare the efficiency of the adsorbents for each of the three metals studied, we prepared synthetic fresh and saline waters with concentrations of precious metals between 5 and 100 ng/L. The adsorbents were subject to analysis using ICP-MS and INAA. In addition, we used electronic and X-ray imaging techniques to gain a better understanding of how the adsorption onto the material occurred.

The adsorption of Au, Pt and Pd showed differences between the adsorbent materials and overall encouraging results. In contrast, Ag results have highlighted that the carbon fabric, contains Ag in its structure while Purolite resins lead to AgCl precipitation. Finally, the very low adsorbency of Ag onto carbon grains makes it unsuitable for exploration with further work needed to find a suitable Ag adsorbent.
Toward a better understanding of Sb metallogeny in the Variscan belt

Anthony Pochon, Eric Gloaguen, Charles Gumiaux, Florence Cagnard, Giada Iacono-Marziano, Johann Tuduri, Hector Campos
ISTO, UMR 7327, Université d’Orléans, CNRS, BRGM, Orléans, France

Denis Gapais, Yannick Branquet, Marc Poujol, Philippe Boulvais
Univ Rennes, CNRS, Géosciences Rennes–UMR 6118, Rennes, France

Through the European Variscan belt, Sb deposits are often spatially associated with gold (as accompanying element or neighboring deposit) and they are classically assigned to orogenic gold systems, because of similar characteristics. Besides, they are sub-contemporaneous with a crustal-scale hydrothermal event linked to late-orogenic extension (~300 Ma). This event likely results from the exhumation of extensive metamorphic domes, which induced a strong temperature gradient and the subsequent metamorphic devolatilization. However, if the metamorphic transition (i.e. from the greenschist to the amphibolite facies) constitutes a probable source of fluids and metals for gold deposits, particularly into the internal zone of the Variscan chain (e.g. French Massif Central), this is much less obvious for Sb deposits, especially within external and unthickened domains (e.g. Armorican Massif and Central Iberian Zone). Indeed, Sb mineralization in the Armorican Massif and Central Iberian Zone shows spatial and temporal links with mafic magmatism emplaced around the Devonian-Carboniferous boundary (~360-350 Ma). Within these unthickened domains, Sb mineralization is therefore likely to be emplaced following mafic magma injections into the upper crust, synchronously with the beginning of the continental collision and before orogenic gold deposition. If the antimony is not directly associated with mafic dikes at surface, it could derive from mafic bodies at depth. We characterized one of these mafic bodies that is now outcropping in the Armorican Massif (the gabbro of Saint-Jean-du-Doigt) and found evidence of Sb-bearing fluids in the central-upper part of the intrusion. We propose that a significant part of Sb and related metals concentrated in the mineralization may come from the fluid phase coexisting with the mafic magma during crystallization. When confirmed, this would emphasize the critical role of early Carboniferous mafic magmatism as a potential Sb source and constitute a major cornerstone for a better understanding of Sb mineralizing systems.
Automated mineralogy applied to a poly-metamorphic terrain: an example from the Archean Vumba Schist Belt, Botswana

Dieter Rammlmair, Dominic Göricke
BGR, Hannover, Germany

The Archean Vumba Schist Belt is situated in the NE of Botswana close to the border of Zimbabwe. This schist belt comprises komatiitic successions, bimodal volcanics, sediments, Archean soils, banded iron formations and rodingites, and is intruded by several generations of granitoids, late pyroxenites, and dolerite dykes. The center and the SE part of the belt host some previously mined shear zone related Au occurrences.

The belt—striking in NW-SE direction—is highly deformed and extremely thinned to less than 10% of its original succession thickness. The belt suffered three pro-grading metamorphic events. The metamorphic center of the first high grade metamorphic event is uplifted due to tilting in the NW, overprinted by a medium grade event shifted to the center. This is subsequently overprinted by the last low-grade event culminating in the SE. This late greenschist facies conditions are responsible for the local anomalous Au redistribution in shear zones.

The metamorphic centers are quasi perpendicular to the strike of ultramafics, mafics and Al-rich sediments. This provides an opportunity to directly compare the expression of metamorphic impact on chemically similar lithologies along strike under different metamorphic conditions.

The main focus was on the gradual change of amphibole and pyroxene chemistry in the mafic rocks related to the metamorphic overprint. Based on previous work, access was provided to several hundred samples along five profiles traversing the belt. The cut hand specimen samples were analyzed by µ-EDXRF M4-Tornado-Plus operating with two detectors to reduce diffraction signals. By employing an ENVI compatible hyperspectral software and a tailored mineral endmember data base, samples were characterized according to their mineral chemistry, modal mineralogy, grain size, mineral assemblages, and where applicable to the Streckeisen nomenclature diagrams. Bulk chemical information was extracted and compared to standard XRF analysis giving a measure of homogeneity of the investigated samples. The study highlights the possibility to apply detailed automated mineralogy based on small changes in mineral chemistry to visualize the progress of complex, quasi isochemical discontinuous regional hydration processes affecting mafic granulites by new assemblages dominated by hornblendes and finally by actinolites from NW to SE throughout the belt with little sample preparation. A future attempt will be to directly attribute metamorphic PT conditions to the chemical diversity of co-genetic mineral assemblages, and to visualize the results in 2D for individual samples.
One meter core! Detailed insight into the Storkwitz carbonatite diatreme, Germany, by µ-EDXRF based automated mineralogy

Dieter Rammlmair, Dominic Göricke
BGR, Hannover, Germany

Manuel Lapp
LFULG, Freiberg, Germany

The Storkwitz carbonatitic diatreme, from the Delitsch complex in Saxony, Germany was investigated for its REE, Nb, Th and U contents. The economic potential is low since REE distribution is complex. One meter of half core of 10 cm diameter, subdivided in 15 cm sub-samples, was scanned by µ-EDXRF M4 Tornado Plus, Bruker-nano under vacuum condition applying a Rh tube at 50kV, 600µA with a poly-capillary beam guide with a spot size of 17 µm at Mo Kα and dwell time of 0.004 sec per pixel. Scanning was performed on 9 sub-areas per sub-sample to achieve full 20 µm step size coverage, and a total of 250 million pixels were obtained. Based on several hundreds of created endmembers of the expected minerals of the system, obtained by samples from the mineral collection and from the drill core itself, a hyperspectral data evaluation with ENVI software applying Spectral Angle Algorithm was performed to classify each pixel and to extract phase distribution maps. The non-carbonatite particles, reaching up to 50 area %, were classified according to modal mineralogy to provide information on the penetrated lithologies, and the area size distribution of fragments. The carbonatite phases, such as phlogopite, apatites, carbonates, REE-phases and pyrochlore were further investigated for their chemical differences and textural relationships. A series of chemically distinct carbonates could be differentiated according to their relationship within the multiple brecciated diatreme, providing relative age information as well as grain size distribution of the embedded fragments. A special focus was on the distribution of REE-phases within the breccia showing a strong relationship to a last fracturing and alteration event and enrichment within open micro-fractures. A proportion 1:1 of rock fragments to carbonatite will enhance the REE, Nb, Th and U values of the pure carbonatite by a factor of two.
Mesoscopic aspects of chromitite from UG2, Bushveld Complex, South Africa

Dieter Rammlmair, Jeannet Meima, Dominic Göricke, Wilhelm Nikonow
BGR, Hannover, Germany

Imaging of element intensities based on µ-Energy Dispersive X-Ray Fluorescence (µ-EDXRF) provide large area information at a spatial resolution in the sub-mm range. Despite some analytical obstacles such as diffraction signals, analyzed volume per pixel, and grain boundaries, µ-EDXRF provides information about systematic changes of the chemistry of individual minerals and their relationship to microstructures. The 70 cm thick UG2 interval of drill core examined here is comprised of mottled chromitite dominated by either orthopyroxene, plagioclase or phlogopite that host idiomorphic to rounded or even agglomerated chromite grains with variable grain sizes from <50 µm to 500 µm. Plagioclase dominant hosts the smallest grain sizes, orthopyroxene the intermediate and phlogopite schlieren the largest. Common to all hosts is that the mean grain size (µm) of chromites shrinks over 70 cm in the younging direction for pyroxene, plagioclase and phlogopite from 170 to 120, 140 to 107, and 240 to 105, respectively. The Cr/(Cr+Al) in chromite relates to the host, whereas Mg/(Mg+Fe²⁺) shows little variation. The phlogopite schlieren show abundant K-feldspar, albite and quartz, locally with symplectites, and are locally enriched in apatite, zircon and monazite. A site-specific endmember database was used for automated mineralogy by supervised classification based on the spectral angle mapper algorithm of the hyperspectral evaluation software ENVI. Detailed information is obtained on mineral distribution, mineral chemistry and neighborhood providing a tool to select key samples for detailed investigation by Electron Probe Micro Analyzer (EPMA), SEM-Mineral Liberation Analysis. The application of µ-EDXRF based automated mineralogy to large samples elucidates mineralogical and textural relationship in a very detailed and objective way, within the limits of the method. Besides primary magmatic features, the degree of late magmatic impact and hydrothermal overprint controlling chromite chemistry can be recognized and perhaps related to a hydrothermal redistribution of Cu-Ni sulfides and associated PGE mineralization.
Replacement or plume fallout? Both, please!
Evidence from active and fossil VMS systems

Jorge M.R.S. Relvas, Fernando J.A.S. Barriga, Álvaro M.M. Pinto, Filipa Marques
Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

João Carvalho
Low Carbon & Resource Efficiency, R&Di, Instituto de Soldadura e Qualidade, Portugal

Ágata Dias
Institute of Science and Environment, University of Saint Joseph, Macao SAR
Instituto Dom Luiz, Universidade de Lisboa, Portugal

The mechanisms of sulfide deposition and mineralization styles are among the main factors that determine the efficiency of VMS systems to produce significant and economically interesting accumulations of massive sulfides. These factors have long been discussed from the perspective of interpreting the size of deposits, their degree of preservation and, indirectly, their metallic ratios. Given the enormous density of its deposits and the variety of its depositional settings and mineralization styles, the Iberian Pyrite Belt offers exceptional conditions to study this subject and establish representative comparisons between different situations. Giant deposits, embracing clusters of many orebodies formed over long-lasting ore-forming processes, constitute excellent laboratories where the different mechanisms of deposition include a wide spectrum of hybrid situations limited by marked endmembers. Furthermore, several active seafloor hydrothermal sites (e.g. Manus Basin, Rainbow, TAG, Seven Sisters) have also provided precious information on scenarios of plume fallout accumulations and sub-seafloor replacement mechanisms, yielding direct evidence of metal deposition either upon, or prior to fluid discharge on the seafloor. Here, we present and discuss examples of both active and fossil systems where plume fallout accumulations of sulfides could be preserved and major metal loss by plume dispersion could be avoided, together with other examples where intensely altered footwall rocks grade upwards into mineralized volumes where complete replacement of the pre-existing rocks for massive sulfides took place. Textural evidence for these depositional processes is overwhelming. At Neves Corvo, mass-balance calculations were undertaken to follow the chemical evolution of the fluid-rock system while alteration progressed from conversion of fresh rhyolites into chloritites, and from these into massive sulfide ore by silicate-sulfide chemical replacement. The characteristics of VMS depositional mechanisms are crucial to trace exploration vectors for productive, trough hidden, hydrothermal sites in the modern seafloor.
Critical elements in fluids of the Taupō Volcanic Zone

Agnes G. Reyes
GNS Science, Lower Hutt, New Zealand

To assess the potential for Taupō Volcanic Zone (TVZ) hydrothermal systems to produce ore deposits and economically-critical elements, chemically-analyzed well discharges were studied and scales from geothermal installations petrographically and chemically-evaluated, with the latter back-calculated to reservoir conditions. More than 50 elements/compounds have been analyzed in the discharge fluids of geothermal systems in the TVZ. Assuming a mass flow of 200 k/h for one typical geothermal system with a 3:7 ratio for gas and aqueous fluids, elements with the highest concentrations (>100 kg/a) in the water, from lowest to highest, include Ge, Sb, W, Sr, Rb, Cs, Mg, V, Li, B, Si and As. Although only <12 kg/a of Tl, Ga, Au and Ag are contained in the discharge fluids, their high market price warrants further study. Amongst gases of economic interest in the TVZ are C₂H₆ and CO₂. Helium is present but the production rate at <1000m³/a is too low to be of interest. Without considering mining, production and research costs, fluids from just one producing TVZ geothermal system contain about NZ$1B/a worth of critical elements. However, as attested by studies of metal and non-metal deposition in geothermal installations and volcanic crater lake deposits, specific conditions are required to induce precipitation of specific elements including, among others, changes in fluid flow rates, redox conditions, temperature and pressure; phase separation and fluid mixing. For example at >200°C, flashing in geothermal installations removes Ag, Au, Te, Cu and Pb from the fluid to form sulfides and tellurides, whilst steam condensation induces deposition of Sb-, Hg- and Mo-rich sulfides. Reducing sulfur-rich conditions suppress metal deposition other than pyrite, whilst oxidizing acidic to near-acidic conditions deposit tenantite, Cu-sulfides, natroalunite and Fe-sulfates. Despite high concentrations of a wide range of critical elements in the TVZ fluids, only a few can be economically extracted at present.
From promises to storytelling: the use of narrative in social risk reduction by a junior mining company in France

Aurélien Reys  
CNRS – Université de Lorraine, UMR 7359, GeoRessources, Mines Nancy, Nancy cedex, France

Julien Merlin  
Univ. Grenoble Alpes, CNRS, Sciences Po Grenoble, Pacte, Grenoble, France

Agnès Samper  
LabEx RESSOURCES21 – Université de Lorraine, CNRS, INRA, OSU Otelo, Mines Nancy, Nancy cedex, France

Sylvain Le Berre  
INRAE, Centre Nouvelle-Aquitaine Bordeaux, UR ETBX

Yann Gunzburger  
Université de Lorraine – CNRS, UMR 7359, GeoRessources, Mines Nancy, Nancy cedex, France

Juniors mining companies are involved in mineral exploration to identify significant mineral deposits in order to sell or joint venture their discoveries to major companies. Such activities are speculative and risky. To achieve their goals, juniors must convince stakeholders of uncertain future profits, investors to provide funding, the public administration to grant an exploration license, and local communities to agree to a social license. To increase their chances of success, they make technical, economic, environmental and social commitments in a process that can be compared to promise engineering.

By following the trajectory of a helium reservoir exploration project in France, this study investigates how the junior company in charge of the project seeks to mitigate social risk primarily through communicating a narrative of promises of eco-friendly and territorially integrated activities rather than building a co-constructive dialogue with local stakeholders. By using such a storytelling-type marketing strategy, the company may pave the road to a new approach for juniors to alleviate social risk which allows us to develop two points. First, our analysis is interested in the variety of mechanisms implemented to support the told story that incorporates numerous references to an eco-friendly and integrated-into-the-territory mining project. Second, we suggest that this storytelling is not only aiming at convincing local communities, but also has financial and political targets. From this perspective, managing social risk through a successful narrative could become a new tool for juniors to increase their chances to get funds or sell their projects to majors. It could also represent a new hope for the French government who has been seeking for a decade to revive mining activities in the country.
Arc magmatism and metallogeny in the Lesser Caucasus and Eastern Pontides: geochronology, geochemistry and geodynamic implications

Hervé Rezeau
Department of Geosciences, University of Arizona, Tucson, Arizona, USA
Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Marc Hässig, Robert Moritz, Massimo Chiaradia
Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Emin Sadikhov
Moscow Institute of Physics and Technology, Moscow Oblast, Russia

The architecture of the present-day Lesser Caucasus and Eastern Pontides regions are the result of a complex magmatic and tectonic evolution related to Gondwana-derived terranes accretion to the southern Eurasian margin from the Paleozoic to Cenozoic. This is characterized by multiple episodes of arc magmatism, opening and closure of oceanic domains, obductions and collisions. As a consequence of this fascinating magmatic and tectonic evolution, these two regions are exceptionally endowed in ore deposits, including polymetallic deposits, volcanogenic massive sulfide deposits, porphyry Cu-Mo deposits and epithermal Cu-Au deposits formed during the Mesozoic and Cenozoic. Here we present a new comprehensive zircon Hf isotopic dataset for key areas along these two regions, including the Kapan zone, the Gedabek district, the Tsarguniats-Meghradzor-Toukhmanouk district, the Alaverdi district, and the Bolnisi district in the Lesser Caucasus and the Elbeyli-Ordu, Emeksen-Giresun, Güzelyayla-Trabzon and Ulutas-Ispir porphyry-type prospects in the Eastern Pontides. Together with a regional compilation of bulk rock element and isotope geochemical analyses, these complementary datasets place spatial, temporal and geochemical constraints on three well-defined magmatic cycles during the Mesozoic and Cenozoic. This comprehensive regional synthesis of the evolution of the geochemistry of arc magmatism across the Lesser Caucasus and Eastern Pontides further helps us to place additional petrological constraints on the current magmatic and tectonic models. Despite some minor differences explained by local features, the main outcome is that the regional evolution of arc magmatism shares consistent geochemical characteristics, which is interpreted as reflecting a common geodynamic evolution. Building on this regional geodynamic framework, the spatial and temporal distribution of ore deposits provides important pieces of information regarding key factors controlling arc magma fertility, which ultimately offers perspectives for new exploration opportunities in the middle section of Tethys ocean.
The influence of host rocks on epithermal veining in the Waihi area of New Zealand

Shannon Richards, Lorrance Torckler
OceanaGold, Waihi, New Zealand

Epithermal deposits are known to be challenging deposit types to explore, though once they are discovered they can often present with high rewards sometimes several decades after their initial discovery. Veins in Waihi have produced >8 Moz of gold and sustained gold mining for 110 of the last 140 years.

In Waihi, mineralization is hosted by five deposits including the large Martha deposit. These all have interesting characteristics that resulted in their discovery and sometimes re-discovery. The veins in Waihi are hosted within a thick package of andesites that can be subdivided texturally into an upper horizon lacking any quartz phenocrysts and a lower horizon that contains quartz phenocrysts. Veins forming the Correnso and Martha deposits are developed almost entirely within the lower andesite. These veins extending up into the upper andesite pinch out abruptly just above the contact. The Trio deposit situated 1 km to the southeast of the Martha deposit, has developed within both the upper and lower andesite units. Historical mining of Trio was confined to the upper andesite where veins had long strike extents but were narrow and did not yield high gold grades. Exploration drilling in the 2000s intercepted the lower andesite at depth hosting wide, mineralized veins that were later mined from underground. The discovery of the Favona deposit situated approximately 1.5 km to the southeast of Martha is hosted solely within the upper andesite, challenging the previous dogma of a preferential host rock for mineralization.

The veins recently discovered at Wharekirauponga in 2017 have developed within a rhyolite flow dome complex. Here, veining is abundant within the rhyolite flows, however vein density and grade decrease dramatically within the surrounding volcaniclastic units. Experience from Waihi has shown that conditions for vein development are different from one vein set to the next.
3D geological modeling of the Black Angel Zn-Pb mine area (Maarmorilik, West-Greenland) and its implications for mineral exploration

Philip Rieger, John Güven, Koen Torremans
Irish Centre for Research in Applied Geosciences (iCRAG), University College Dublin, Belfield, Dublin, Ireland

Mark Holdstock, Justinas Matusevicius
Black Angel Mining A/S (BAMAS) Qullilerfik 2, 6, Nuuk, Grønland

Frank van der Stijl, David Coller
Independent Consultants

Pierpaolo Guarnieri, Nigel Baker, Eric Vest Sorensen
Geological Survey of Denmark and Greenland (GEUS), Øster Voldgade 10, Copenhagen K, Denmark

Proterozoic sedimentary basins are among the most important repositories for Zn and Pb and therefore highly prospective regions for mineral exploration. In the Maarmorilik area in West-Greenland, the Paleoproterozoic Karat Group is host to the Black Angel Zn-Pb deposit (historic production: 11.2 Mt at 12.4 wt% Zn and 4.2 wt% Pb), and >200 mineralized showings. The deposit is hosted by greenschist facies metamorphic calcitic and dolomitic marbles of the Mârmorilik Formation, which have undergone several phases of deformation, superimposed onto the extensional basin stratigraphy. Previous geochemical, structural and petrographic research indicated ore formation via host rock replacement and a strong structural and stratigraphic control on mineralization. This structural-stratigraphic control, however, is not well understood. We present results of first-ever 3D structural-stratigraphic and orebody modeling of the Black Angel area, based on integrated historical mine sections and plans, regional mapping, surface, and underground drill hole databases. The subsurface structure and horizon models are combined with 3D-photogeology based on high-resolution oblique photos of Black Angel Mountain and Nunngarut. Basal quartzites, meta-pelites and various altered marbles and calc-silicate rocks of the Mârmorilik Formation comprise structural domains with extensive zones of continuous semi-planar units showing boudinage, pinch-and-swell, and domino-fault features at zones of normal and reverse faulting, as well as zones of complex tight to isoclinal, occasionally recumbent NW-WNW trending folding. Strain in the latter is often partitioned into relatively discrete areas. At regional scale, thrusting occurs both involving and not involving basement. Analysis of Zn, Pb and Fe grades reveals WNW trending orebodies, hosted in different parts of the stratigraphy. Highest grades of tectonically reworked ore generally trend parallel to the NW-WNW zones. This study highlights how comprehensive 3D subsurface and outcrop geological modeling utilizing multiple data sets can help to understand the tectonostratigraphic framework of highly complex and deformed basin-hosted mineral systems.
The Dolphin tungsten deposit is located at Grassy, King Island, Tasmania. The tungsten ores, which consist of scheelite-bearing garnet-pyroxene skarns replacing Neoproterozoic carbonate rocks that are overlain by tholeiitic volcanics, are related to the intrusion of the Carboniferous Grassy granodiorite. Overall reserves of the Dolphin mine are 4.43 Mt @ 0.92% WO$_3$ (King Island Scheelite Ltd 2020). Tungsten is the only metal recovered, but the ores also contain ~0.03% molybdenum, in the form of molybdenum-rich scheelite and minor molybdenite.

Tungsten skarn mineralization formed in carbonate rocks adjacent to brittle faults and dykes that emanated from the main granitoid. There are two main tungsten ore horizons, B Lens and C Lens, both ranging from 10-30 m thick. C Lens hosts the best tungsten mineralization, which has several distinct mineralogical components including garnet hornfels, pyroxene-garnet hornfels, and banded pyroxene-garnet hornfels. B Lens is an upper dolomite horizon that has been variably hornfelsed and metasomatized with sporadic mineralized pyroxene-garnet skarn.

Based on detailed petrography, open pit mapping, drill hole logging, downhole gravity, and magnetic survey data, and 3D visualization modeling, we have built a detailed geological and geophysical model for the Dolphin W deposit, and a virtual 3D tour of the Dolphin open pit. The virtual tour provides geoscientists and explorers with the opportunity to explore the geology, mineralogy, structure and geochemistry of the Dolphin orebody in considerable detail and should prove to be a valuable training resource for skarn explorers and researchers globally.
Iron oxide-apatite (IOA) deposits as potential vanadium sources

Maria A. Rodriguez Mustafa, Adam C. Simon
University of Michigan, USA

Jihua Hao
University of Science and Technology of China, China

Mark Frank
Northern Illinois University, USA

Austin Gion
University of Orléans, France

Vanadium is a critical element necessary in steel alloys and in V redox batteries, both of which are essential for the development of low-carbon energy infrastructure. Vanadium is traditionally a by-product of the extraction of Fe and Ti in magmatic deposits and of U in sedimentary hosted U-V deposits. Its demand is forecasted to increase significantly, so new sources of this element will be needed to achieve the required supply. Iron oxide-apatite (IOA) deposits are dominated by magnetite, an iron oxide mineral. They are major sources of Fe and recent studies have shown that they can contain substantial V hosted in magnetite too. This project explores the favorable physicochemical conditions for the formation of V-rich magnetite in these deposits.

Magnetite in IOA deposits is thought to result from magmatic-hydrothermal processes but the exact conditions of the hydrothermal fluid from which it precipitates are still unclear. We present the thermodynamic modeling of aqueous speciation of a hydrothermal fluid that exsolves from a melt of intermediate composition. Our model evaluates the behavior of V-species in the fluid as a function of temperature, pressure, pH and fO₂. Our preliminary results indicate that V is most favorably incorporated in magnetite as V³⁺ at high temperature and low pH and fO₂.

Our results indicate that hydrothermal magnetite can host considerable amounts of V in its structure and that the parental melt for the hydrothermal fluid needs to be of intermediate composition. These results have implications within the tectonic setting that is suitable for the formation of IOA deposits, which will allow for improved exploration campaigns to find this type of deposit more efficiently to increase the resources of V needed for the energy transition.
Inherited structures and golden triggers: controls on the localization of Cretaceous-to-Recent gold deposits, Aotearoa New Zealand

Julie V. Rowland
The University of Auckland, Auckland, New Zealand

New Zealand’s precious metal endowment is linked to pulses of hydrothermal activity resulting from magmatism, metamorphism and tectonism along an evolving accretionary orogen within the continent of Zealandia. In the North Island, the orogen is under extension and Miocene-to-Recent Au-Ag epithermal deposits and environments are documented in Northland, the Coromandel (Hauraki Goldfield) and the Taupō Volcanic Zone. Conversely, in the South Island, the orogen is under contraction, and Cretaceous-to-Recent orogenic Au±W±Sb deposits and environments occur within Otago, the Alpine zone, and Marlborough. These disparate styles of mineralization appear confined to a corridor that parallels the New Zealand orocline and associated Mesozoic convergent margin, and which, from Otago to southern North Island, coincides spatially with a rheologically-weak metamorphic overprint – the Haast Schist. The timing of mineralization and tectonic events suggests that major disruptions at the convergent margin episodically triggered metal supply into a crustal-scale metal-transfer superhighway, resulting in diachronous distribution of gold and companion metals (including critical minerals) within the orogen.

For most of the Cenozoic, mineralization occurred on structures that were active when the New Zealand orocline, defined by a series of narrow, elongate Mesozoic terranes, was parallel to the plate boundary. In these settings (e.g. Otago, northern Coromandel, Northland), the dominant strike of vein-style deposits is parallel to the orocline. However, by the late Miocene, a new subduction margin at high angle to the orocline had developed in the North Island and the dominant strike of epithermal veins swung into alignment with the prevailing arc. Nonetheless, deposits appear to be localised where deeper-seated inherited structures tectonically-segment rift basins. Taken together, the active epithermal environments of the Taupō Volcanic Zone and the epithermal deposits of the central and southern Hauraki Goldfield align along the northward projection of the Haast Schist, assuming it follows the pattern of other Mesozoic terrane markers.
Experimental modeling of Cu and Ag coupled transport by chloride hydrothermal fluids at 350–450°C and 1000 bar
Ekaterina A. Rubtsova, Boris R. Tagirov
Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry RAS
Irina Yu. Nikolaeva, Maria E. Tarnopolskaya
Department of Geology, Lomonosov Moscow State University
Mineralization in porphyry Cu deposits is formed by chloride-bearing fluids of a wide Cl concentration range, from a few wt.% to 50 wt.% NaCl eq. In order to quantify the hydrothermal mobility of Cu, we performed an investigation of the speciation of Cu in chloride-bearing fluids using solubility determinations. For this purpose, the coupled solubility of Cu and Ag was determined in acidic chloride solutions at 350 and 450°C and 1000 bar using the autoclave technique with the determination of dissolved metal contents after quenching. The method avoids the control of the most important parameters of the system, f(H₂), pH and chloride activity. The fluid composition varied from diluted HCl-bearing (0.1 m HCl) to NaCl-bearing (0.01-0.02 m HCl + 0.2-15 m NaCl). The measured concentration of Cu was 2-2.5 log units higher than the concentration of Ag. The solubility data over the entire Cl concentration range is accurately described by the reaction Cu(0) + AgCl₂⁻ = Ag(0) + CuCl₂⁻, which implies that CuCl₂⁻ is the dominant complex of Cu in all the experimental fluids. The reaction constant, log K(Cu–Ag), decreases with increasing temperature from 2.7 ± 0.4 at 350°C to 2.3 ± 0.2 at 450°C. Therefore, the difference in the stability of CuCl₂⁻ and AgCl₂⁻ becomes less pronounced with increasing temperature. Combination of the reliable literature values of the AgCl₂⁻ formation constant with log K(Cu–Ag), determined in the present study yields the Cu solubility constant Cu(0) + HCl° + Cl⁻ = CuCl₂⁻ + 0.5H₂(aq), log K(Cu), which increases from 1.5 ± 0.4 at 350°C to 1.9 ± 0.2 at 450°C. These results imply that the forms of occurrence of Cu and Ag in high temperature hydrothermal fluids are similar. The main aqueous species of these metals are CuCl₂⁻ and AgCl₂⁻, their predominance fields extend from diluted Cl-bearing fluids to the NaCl saturation limit.

A new genetic model for marine ooidal iron ore deposits in Western Siberia, Russia
Maxim Rudmin
Division for Geology, School of Earth Sciences & Engineering, Tomsk Polytechnical University, Russia
This study investigates the authigenically formed ironstones within the Upper Cretaceous and Paleogene marine ironstone in Western Siberia (Russia). The West Siberian ironstone basin consists of the Upper Cretaceous (Kuznetsovo, Ipatovo, Slavgorod, Gan’kino) and Paleogene (Lyulinvor) Formations, with three main ore horizons. The predominantly marine succession comprises ooidal or peloidal ironstones, glauconitolites, glauconitic rocks, and sandstones, siltstones, claystones and gritstones. The ooidal ironstone comprises predominantly abiogenic precipitates with subordinate microbial signatures, including micro-oncoids, relicts of lipids, carbohydrates and microfilaments. Iron-rich ooids, peloids and micro-oncoids formed primarily by adsorption and rarely by bacterial action. The abiogenic formation of ooids and peloids depends on geochemical conditions during ion adsorption. While berthierine-goethite in the ooid cortex formed in an oxic or dysoxic environment, siderite laminae within them represent formation under anoxic conditions. Microbial mediation influenced the precipitation of berthierine and goethite, pyrite, siderite, greigite, pyrrhotite, wurtzite, barite, As-Ni-Co-Fe sulfides, and probably monazite or rhabdophane. Siderite, pyrite, and to a lesser extent greigite and pyrrhotite formed exclusively within organic remains. Goethite with a high content of phosphate and berthierine within micro-oncoids probably formed by the activity of iron-reducing bacteria. Bacterial microfilaments within micro-oncoids appear similar to thermophilic cyanophages. Raman peaks of lipids and carbohydrates strongly support a bacterial origin of micro-oncoids. The abiogenic and bacterially induced precipitates reflect the activity of cold seeps, which led to the formation of the ooidal iron ore deposits. The abundant intraclasts at the base of the Ipatovo Formation, marking the Coniacian-Santonian boundary, and at the Lyulinvor Formation, marking the Palaeocene-Eocene boundary, correspond to active tectonics, causing an enhanced supply of metal-rich nutrients. Detailed mineral geochemistry supports a hydrothermal source of iron and other metals for iron-rich ooids and peloids in Western Siberia.
New insights into origin of Oligocene channel ironstone deposits in Turgay depression

Maxim Rudmin
Division for Geology, School of Earth Sciences & Engineering, Tomsk Polytechnic University, Russia

Channel ironstone deposits represent a unique variety of iron-rich sedimentary rocks, which are mostly found in Northern Kazakhstan and Western Australia. The origin and depositional conditions of this rare deposit type are poorly understood. This study investigates the derivation of the Lisakovsk ironstone deposit in the Turgay depression, by assessing the iron source(s) and the palaeo-depositional conditions. Four lithofacies representing fluvial and deltaic channel environments have been identified. Ooids, peloids and micro-oncoids are allogenic, while proto-ooids formed authigenically. (Hydro-)goethite and botryoidal cement formed during the last stage of the diagenesis. Upper Cretaceous marine ooidal ironstones are the main iron source for the Lisakovsk deposit and provided most of the metal content. Major oxides and trace metals elements of the Lisakovsk ironstone are derived primarily from the cement in this underlying marine ironstone. However, the rare earth elements patterns reveal a complex origin of the channel ironstone deposit, including hydrogenic and diagenetic signatures. The Lisakovsk deposit formed in three stages. The first stage involved the uplift and erosion of Cretaceous ironstone and the establishment of palaeo-drainage pattern along major faults. During the second stage, iron-rich detritus was redeposited along fluvial channels. The cement of the original ironstones was dissolved, while ooids, peloids and micro-oncoids remained stable phases in the fluvial and deltaic channel environments. In the final stage, ironstone cementation with proto-ooids and rare metals took place during the early and last phases of diagenesis.

Application of spatial point pattern analysis of porphyry copper deposits in Kerman Belt, southeastern Iran

Sareh Sadigh, Mirsaleh Mirmohammadi
School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran

Omid Asghari
Simulation and Data Processing Laboratory, School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran

Alok Porwal
Centre for Studies in Resources Engineering, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra, India

Spatial point pattern analysis of mineral deposits in a metallogenic province provides valuable information about the underlying geological controls, and hence can help in discovering new deposits in the province. In this study, average nearest neighbor and K function algorithms were applied to the Kerman metallogenic belt, southeastern Iran, in order to understand the spatial distribution of porphyry copper deposits. Further, the fractal analysis was applied to understand spatial distribution patterns of the deposits at different scales. The results indicate significant clustering among the deposits. The fractal analyses indicate that the spatial distribution of the deposits is controlled by different controls at the scales of 5 to 13 km, 13 to 80 km and >80 km.
Critical metals concentration from mine wastes in Mexico, Chile and Australia: a data integration approach

Enrique Sáez-Salgado¹, Denys Villa Gomez², Olivia Mejías¹, Anita Parbhakar-Fox¹, Laura A Pinedo-Torres³, Laura Jackson¹ and Aurora M Pat-Espadas⁴

¹ Sustainable Minerals Institute, University of Queensland, Indooroopilly, Queensland, Australia
² School of Civil Engineering, University of Queensland, Lucia, Queensland, Australia
³ Instituto Politécnico Nacional Zacatecas, Zacatecas, México
⁴ CONACYT-UNAM Instituto de Geología, Estación Regional del Noroeste, Hermosillo, Sonora, Mexico

The mining industry has faced many well-documented challenges. Several are inherent to every worldwide extractive business, but others are specific to the industry, such as the higher demand for renewable sources of energy and greener processing technologies. Mexico, Chile and Australia are three mining countries with challenges regarding acid and metalliferous drainage production from mine waste coupled with the desire to increase critical metal production. The focus of this research, an international collaboration, is to create an open-access website to unify all publicly available data on the geochemical properties of mine tailings contained in these countries. This platform will provide vital information to governments, academia and mining companies, and other interested stakeholders.

Each country is at a different stage regarding sites identification, characterization and potential for critical metals and raw materials with high economic importance, based on a potential ratio calculated. Chile has one of the highest identified sites, with over 642 deposits with 2,032 samples, while Mexico has 159 characterized sites but with data mainly focused on metals that pose environmental concerns. Early data assessment indicates that Chile has significant potential for Sb, Bi, W and Mo, mostly from northern to central regions and Zn to the south; meanwhile, Y, Co, Cr, Hf, Ta y V could be considered minor potential. In contrast, Mexico has significant potentiality for Bi, Sb, W, In, Zn and Mo in Sonora State. Whilst data from Australia is still being compiled, the potential for Co from IOCG and sediment-hosted deposits has been recognised in Queensland State with In concentrating on mine waste derived from VHMS systems. The research exposes that the available information is insufficient, and therefore more data is needed to state the real potential of tailings as a promising secondary source of these elements.
Giant Co-Ni arsenide mineralization resulting from cold hydrocarbon seep and Upper Devonian brine circulation in Neoproterozoic serpentinite (Bou Azzer, Morocco)

Nicolas J. Saintilan\(^1\), Stefano M. Bernasconi\(^2\), Moha Ikenne\(^3\), Julien M. Allaz\(^1\), Mustafa Souhassou\(^4\), Abdelhak Karfal\(^5\), Lhou Maacha\(^6\), Jorge E. Spangenberg\(^6\)

\(^1\)Institute of Geochemistry and Petrology, ETH Zürich, Zürich, Switzerland
\(^2\)Geological Institute, ETH Zürich, Zürich, Switzerland
\(^3\)LAGAGE, Faculty of Sciences, Ibn Zohr University, Agadir, Morocco
\(^4\)EGERNE, Polydisciplinary Faculty of Taroudant, Ibn Zohr University, Agadir, Morocco
\(^5\)CTT - Bou-Azzer Mine- Managem Group, Twin Center, Casablanca, Morocco
\(^6\)Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland

Genetic models for Co-Ni-Fe arsenide mineralization in an accepted context of extensional tectonics remain controversial. Published evidence of mineralogy, mineral chemistry, and fluid inclusion microthermometry and microchemistry studies were reconciled based on the pivotal understanding of (1) the dynamic and fast reduction of As- and Co-Ni-Fe-bearing hydrothermal fluids, and (2) the required basic pH conditions at low fugacity of H\(_2\)S. Yet, additional constraints on (1) the role of host rock chemistry, (2) the source of As, and (3) the absolute timing of arsenide mineralization are necessary to reach an overall consensus. Here, we present new (1) rhenium-osmium (Re-Os) isotope geochemistry data for safflorite combined with (2) clumped, carbon (d\(^{13}\)C V-PDB) and oxygen (d\(^{18}\)O V-SMOW) isotope data for its calcite gangue, and (3) mineral-specific sulfur isotope compositions (d\(^{34}\)S V-CDT) of rammelsbergite (1.63 wt.% S) and safflorite (1.18–2.25 wt.% S) in this paragenetic order at Bou Azzer, Morocco. Safflorite may have formed at 369.8 ± 3.1 Ma (Upper Devonian; preliminary Re-Os isochron age, \(n = 6\)) and at low temperature (\(T_{\text{minimum}} = 138 ± 12°C\) to 177 ± 13°C, 95% confidence interval, \(n = 36\)). The d\(^{18}\)O values of the hydrothermal fluid in equilibrium with calcite (−1.04 to +1.99‰) are compatible with brines derived from Upper Devonian seawater (d\(^{18}\)O\(_{\text{seawater}}\) = −0.10 ± 1.30‰). Brines could have leached Os (initial 187\(^{187}\)Os/188\(^{188}\)Os ratio in safflorite = 0.120 ± 0.001), and by corollary, other metal(loid)s, from Neoproterozoic serpentinite. The rather uniform negative d\(^{13}\)C values of calcite (−4.21 ± 0.27‰, 1SD, \(n = 36\)), which are within the d\(^{13}\)C range of carbonates in sediment-hosted petroleum reservoirs worldwide, and the negative d\(^{34}\)S values of rammelsbergite and safflorite (−8.31 ± 0.19‰, \(n = 4\); −7.63 ± 0.14 to −5.21 ± 0.07‰, \(n = 4\), 1SD, respectively) are compatible with hydrocarbons previously identified in calcite.
Indicator minerals and geochemical footprints in cover over the Nova-Bollinger Ni-Cu-Co sulfides, Western Australia

Walid Salama, Robert L. Thorne, Ravi Anand, Aaron Davis
CSIRO Mineral Resources, Kensington, Perth, Western Australia

The Nova-Bollinger Ni-Cu-Co sulfide deposit is located approximately 200 km southeast of Kalgoorlie within the Albany-Fraser Orogen in Western Australia. The mineralization is associated with an eye-shaped, metamorphosed mafic-ultramafic sill complex and covers an area of 2.4 x 1.2 km with a maximum depth of about 450 m. The surface regolith is characterized by saprolite with variable thicknesses (5-70 m), most likely related to variations in the bedrock lithology and structure. Saprolite is overlain by thin transported cover (<5 m) of puggy sandy clay colluvium with iron granules and calcrite, except for areas of paleochannels east of Nova deposit, where it reaches up to 55 m. The saprock is very close to surface or in some instances is exposed, particularly to the west of the Nova deposit. The Nova mafic intrusion is defined by Ni, Cu and Co anomalies that are restricted at surface and broader in the saprolite. Anomalous Cu concentrations found in the bedrock outside the mapped mafic intrusions may be related to faults that act as conduits for fluid bringing Cu to the surface. Elevated Cu concentrations away from the mafic intrusion in the saprolite and transported cover may be related to both underlying elevated Cu concentrations as well as hydromorphic dispersion and secondary sulfide formation in paleochannels. Heavy mineral analysis was undertaken above the unconformity (interface) between the in-situ and transported regolith. The results show pyrrhotite, chalcopyrite and pentlandite are preserved during the weathering process and occur as detrital phases over the mineralization. Secondary chalcopyrite, pyrite and marcasite have formed at the base of the paleochannel. Weathering of the chalcopyrite in the shallower oxidized part of the paleochannel has formed covellite. There is the potential for the physical transport of detrital sulfides and associated gossan fragments along the gently inclined interface resulting in broader exploration targets.
New mapping protocol using a rapid response cell (fast-funnel) for laser ablation coupled to a time-of-flight mass spectrometer (LA-FF-ICP-TOF-MS) for the fast, simultaneous quantification of multiple minerals

Dany Savard, Paul Bédard, Sarah Dare, Sarah-Jane Barnes  
LabMaTer, Université du Québec à Chicoutimi, Chicoutimi, Quebec, Canada

Joseph Petrus  
Harquail School of Earth Sciences, Laurentian University, Sudbury, Ontario, Canada

Michael Shelley  
Laurin Technic Pty Ltd, Canberra, Australian Capital Territory, Australia

Ashley Norris  
Norris Scientific, Kingston, Tasmania, Australia

In situ analysis conducted by LA-ICP-MS for the determination of trace elements provides precious information of chemical composition in a variety of minerals at the micrometer-scale. To date, most laser studies use quadrupole mass spectrometers (ICP-Q-MS) for the analysis of monomineral phases, using static spot or line scan, while chemical mapping can reveal key information such as growth zoning, exsolutions, micro-veins, resorption and more. However, peak jumping mode operation of ICP-Q-MS limits the acquisition speed and spatial resolution. Time-of-flight mass spectrometers (ICP-TOF-MS) can extract full mass range simultaneously at high rate (33 kHz), making the instrument attractive for routine analysis and allowing us to take steps towards new research areas (e.g. 3D mapping). A new protocol was developed using a 193 nm LA-system (RESOlution, Applied Spectra), equipped with a double-volume S-155 ablation cell (Laurin Technic) and a small volume fast-response funnel device (Norris Scientific and Laurin Technic) allowing highly efficient transport of the aerosol to the attached ICP-TOF-MS (TOFWERK). Simultaneous quantification of major and trace elements of various minerals (silicates, sulfides, oxides, apatite and calcite) within single data processing, and without saturation of the ICP-TOF-MS detector, can be achieved by combining multiple calibration materials of varied matrices (glasses, sulfide, apatite). Based on normalization of major elements (without the use of an internal standard), a new data reduction scheme was used, the “3D-trace elements DRS” (IOLITE v4 software). The DRS can recognize the nature of each pixel to adjust the normalization summation according to the phases, such as taking into account undetectable stoichiometric CO₂ in calcite, and an appropriate conversion factor for iron in sulfides (not being bound to oxygen in these phases). Using a rectangle beam of 12 x 6 µm in raster or boustrophedon mode, maps of 12 µm pixels in size are produced and a 1 mm² area is covered in about 10 minutes.
Mineral zonation at the Ernest Henry IOCG deposit—new insights of ore formation by integration of mineralogy, geochemistry and petrophysical data

Tobias U. Schlegel, Renee Birchall, James R. Austin, Helen McFarlane, Jessica Stromberg, Belinda Godel, Andreas Björk, Mark Pearce
CSIRO Mineral Resources, Perth, Western Australia and Lindfield, New South Wales, Australia

The Ernest Henry breccia-pipe hosted Cu-Au deposit is one of Australia’s major iron oxide-copper-gold systems. Previous research interpreted that the deposit formed via the release of magmatic volatiles followed by hydrothermal-phreatic brecciation and precipitation of magnetite and Cu-sulfides in the breccia matrix filling the interstices among syn-ore K-feldspar + biotite + magnetite altered clasts. We present SEM-based modal mineralogy of 262 samples from the deposit, detailed petrography including characteristic mineral replacement textures determined from mineral maps, and the spatial distribution of mineral assemblages in and around the deposit. The mineral data are combined with results from measurements of anisotropy of magnetic susceptibility, geochemical and petrophysical analyses, and high-resolution X-ray computed tomography to present an alternative model of deposit formation. Hydrothermal alteration resulted in a mappable zonation of mineral assemblages and petrophysical properties within and around the ore body. Characteristic mineral halos of feldspars, micas and chlorites, as well as individual minerals such as pyrite and apatite envelope the ore body and extend up to hundreds of meters beyond its limits into the host rocks. The zonation is the result of a sequence of iron oxide-alkali-calcic alteration, shearing, tectonic brecciation, carbonatization, and a previously unrecognized hydrolytic alteration component which was coincident with the Cu-Au mineralization. Hydrolytic alteration reactions increased the porosity via fluid-rock interactions resulting in increased permeability, for example the replacement of magnetite by hematite according to: \( \text{Fe}_3\text{O}_4 + 2\text{H}^+ = \text{Fe}_2\text{O}_3 + \text{Fe}^{2+} + \text{H}_2\text{O} \) with \( \Delta V = -32 \% \). In contrast, hydrothermal replacement of K-feldspar and biotite by chlorite at the breccia margins and in bounding shear zones reduced the porosity and likely the permeability. These and similar mineral replacement reactions resulted in a rim of alteration minerals sealing the zone of Cu-Au mineralization and led to fluid-focusing and the formation of the pipe-shaped ore body.
Integrated geochemical, sedimentological and structural interpretation of the Palaeoproterozoic Granites-Tanami Orogen – vectoring towards gold mineralization

Susanne Schmid, Helen McFarlane, Teagan Blaikie, Marcus Kunzmann
CSIRO Mineral Resources, Perth, Western Australia, Australia

The Palaeoproterozoic Granites-Tanami Orogen in central Australia is an important orogenic gold province. Gold mineralization is hosted by structurally-controlled epigenetic quartz veins with a suggested mineralization age of ~1805 and ~1795 Ma associated with granitic intrusions. The quartz veins are emplaced in the Tanami Group, which consists of mostly lower-greenschist metamorphic grade volcaniclastic-sedimentary rocks and basalts. The Tanami Group depositional age is between ~1912 and 1850 Ma and was deposited in an oceanic back-arc basin setting. Due to lack of exposure and the complex structural setting, the stratigraphic evolution of this basin is poorly understood, and regional stratigraphic correlations are difficult. Here we present sedimentological interpretations together with newly developed geochemical tools and couple structural interpretation of aeromagnetic data for regional-scale correlation. High field strength elements (HFSE) were used to classify (~20,000 analyses) mafic to felsic igneous and volcaniclastic-sedimentary successions across the Granites-Tanami Orogen, revealing a progressive change from mafic- to felsic-sourced provenance with younging of the volcaniclastic-sedimentary rocks. The vectoring led to identification of gold-hosting lithologies with particular geochemical signatures and associated alterations.

Structural interpretation, in association with geochemically defined lithologies, revealed that the decrease of magnetic response generally relates to a change in geochemical composition from mafic to felsic. This allows identification and mapping of favourable lithologies in areas with good geochemical and geophysical data coverage and lack of surface exposure for exploration.

The Neoarchean Carajás IOCG system, Brazil, in the light of the crustal evolution of the Amazonian craton

Maria Emilia Schutesky, Claudinei Gouveia de Oliveira
Universidade de Brasília, Brazil

The Carajás Mineral Province (CMP), Brazil, comprises the oldest iron oxide copper–gold mineralizing system on Earth and is one of the world’s most significant clusters of large-tonnage IOCG deposits. Based on a critical assessment of the literature we discuss a new integrated model for the Carajás Neoarchean IOCG deposits. The model considers the hydrothermal alteration footprint and the rock textures, the geometry of the mineralization and the ore assemblage, and the isotopic and geochronological signature. Most of the deposits form in the hypozonal domain. Pervasive and well-developed sodic (−magnesian) and calcic-iron hydrothermal alteration halos form through magmatic-derived hydrothermal fluids. The occurrence of hydrothermal orthopyroxene-marialite and fayalite-hedenbergite extend the P-T boundaries to temperatures of up to 700°C and >5 kbars, thus corresponding to the root zone of the system. The ore mineralogy is consistent; magnetite is the only iron oxide formed and precipitated from iron-rich hydrothermal alteration accompanying the calcic alteration. Similarly, chalcopyrite represents the main Cu sulfide, with minor bornite. There is no transition to more oxidized assemblages towards shallower zones, supporting that the overall system was relatively reduced. Finally, the stable isotopic signature (S-O-H) compiled from the literature reveals that the fluids are dominantly magmatic. Thus, the Neoarchean Carajás IOCG system represents a crustal-scale continuum, of a vertical paleo-hydrothermal system formed coevally to the voluminous hybrid magmatism and the formation of the world-class, banded iron formation-hosted iron ore. However, due to the protracted tectonic history of the Amazonian Craton, the Neoarchean IOCG were further remobilized during at least three province-scale episodes, at ca. 2.55 Ga, ~2.2−2.1 Ga and ~1.90−1.8 Ga. Late thermal imprint, fluid-induced remobilization, or even deformational events resulted in spatially-related mineralizations, but showing a distinct mineralogical-textural association, fluid signature, and geochemical and isotopic affinities.
Characterization of gold mineralization at the Tau orebody, Mupane, Botswana

Onameditse Seaba, Akira Imai
Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University

Kemmonye Baliki
Mupane Gold Mine, Botswana

The Tati Greenstone Belt in the north-eastern part of Botswana hosts numerous small gold occurrences that are understudied and appear to exhibit a complex genesis. The present research investigates the origin of the Tau orebody in the Mupane gold deposit, hosted in the Archean Tati belt succession, based on ore petrography, geochemistry of the host rocks, and mineral chemistry of sulfides. Arsenopyrite-rich zones are associated with biotite-chlorite veins indicating that the precipitation of arsenopyrite has been concomitant with potassic alteration. Based on textural relationships and chemical composition, early arsenopyrite is sieve-textured with abundant inclusions of pyrrhotite. It is overgrown by late arsenopyrite, which commonly rims the earlier arsenopyrite generation and shows no porous texture and only rare inclusions of pyrrhotite. Sulfidation proceeded via coupled dissolution-reprecipitation reactions as evidenced from porous sulfide inclusions in pyrrhotite. Epigenetic gold mineralization formed via sulfidation of oxide facies BIF. Our observations revealed two stages of gold mineralization within the Tau orebody commencing with the deposition of invisible gold in arsenopyrite. This was followed by the later formation of native gold during hydrothermal alteration and post-depositional recrystallization of arsenopyrite, which also affected the distribution of other trace elements within the grains. The range of δ34S of gold-bearing assemblages from the Tau orebody is restricted from +1.6 ‰ to +3.9 ‰, which is typical of Archean orogenic gold deposits. The results from this study suggest that gold mineralization originated from a magmatic or mantle source through various processes that included sulfidation, metamorphism, deformation, hydrothermal alteration and gold remobilization.

Expanding the perspective on mine waste value with an emphasis on critical minerals and environmental mitigation

Robert R. Seal II, Nadine M. Piatak, Sarah Jane O. White, Sarah M. Hayes
U.S. Geological Survey, 954 National Center, Reston, Virginia, USA

Meeting increased demand for critical minerals and reducing the waste footprint of mine waste can be compatible activities. Opportunities vary based on deposit type and whether a critical mineral is recovered as a primary, co-product, or by-product commodity. A suite of tailings samples is used to evaluate the potential for critical mineral, and base- and precious-metal recovery. For example, Te concentrations are highest in tailings from porphyry Cu deposits and Au deposits. Nickel and Co concentrations are highest in tailings from mafic magmatic deposits, although tailings from other deposit types are also elevated.

A mass-balance approach at a porphyry Cu mine describes the deportment of critical minerals and other commodities in concentrates and tailings during ore processing and enables targeting specific waste streams for additional recovery. Half the Au, Ag, Zn, PGMs, Se and Sb in the ore is lost to tailings. Two-thirds of the Te and most of the Co and REEs also reside in the tailings. The chalcophile nature of Au, Ag and other commodities suggests pyrite as their host.

Waste streams can have additional, potential non-traditional value by reducing environmental costs and from carbon credits. For example, the importance of pyrite as a host of Au and other critical minerals commodities highlights the potential for recovering a pyrite concentrate to improve Au and critical mineral recovery while simultaneously enhancing long-term environmental management by concentrating acid-generating potential in a smaller, more manageable volume. Critical minerals commonly associated with mafic host rocks include PGMs, Ni and Co. The tailings and other mine wastes from these ores are dominated by olivine, pyroxene and calcic plagioclase, which are prime targets for mineral carbonation – a potential source of carbon credits. Thus, the most tenable scenarios to enhance value of mine waste will likely combine resource recovery with improved environmental management.
Formation of the titanomagnetite deposit in Yeoncheon, South Korea

Jieun Seo, Seon-Gyu Choi, Young Jae Lee
Department of Earth and Environmental Sciences, Korea University, Korea

The Yeoncheon deposit is located in the northern part of the Gyeonggi Massif, South Korea. The titanomagnetite ore bodies occurred within gabbroids, which show an inclined elliptical squeezing pipe shape. This Neoproterozoic gabbroic rocks are partly affected by contact metamorphism and alteration by Cretaceous intrusions. The mafic rocks are divided into gabbro (<10 vol.%) and Fe-Ti(-P) ore (>10 vol.%) based on opaque mineral contents. The ‘gabbro’ exhibits variation from melagabbro to quartz monzonite, and ores are subdivided to Fe-Ti and Fe-Ti-P ores by their apatite concentrations. The melagabbro mainly contains clinopyroxene, plagioclase, apatite and amphibole, and minor olivine, orthopyroxene, sphene, serpentine, biotite, Fe-Ti oxides and sulfide minerals, whereas quartz monzonite contains mainly felsic minerals such as quartz, K-feldspar, zircon and allanite. The ores have Fe-Ti oxide minerals (magnetite, ilmenite, titanomagnetite, ulvöspinel), sulfide minerals (pyrite, chalcopyrite, pyrrhotite, sphalerite), and large amounts of apatite. The titanomagnetites have many exsolution lamellae and inclusions such as ilmenite and ulvöspinel. Fe-Ti oxides commonly occur as interstitial phases between silicate minerals, indicative of their relatively later crystallization. The Fe-Ti(-P) ores contains 60‒68 wt.% Fe$_2$O$_3$, 17‒19 wt.% TiO$_2$, 0.1‒0.2 wt.% P$_2$O$_5$. The fractionation of the Yeoncheon Fe-Ti-P rich mafic magma (gabbroic and nelsonitic immiscible magma) exhibits a typical tholeiitic trend.

The Yeoncheon titanomagnetite ores are spatially associated with gabbro formed from a Fe-Ti-P rich mafic magma at 848.6 Ma. The gabbroic and nelsonitic immiscible magma complex has experienced separation. Simultaneously, gabbroic magma crystallized from melagabbro to quartz monzonite by fractionation, and the nelsonitic magma formed Fe-Ti ore and Fe-Ti-P ore (nelsonite) by gravity settling.

Aluminum phosphate-sulfate (APS) minerals: a new potential exploration tool in porphyry – high-sulfidation epithermal deposits

Xin Ni Seow, Lejun Zhang
Centre for Ore Deposit and Earth Sciences (CODES) and Australian Research Council Industrial Transformation Research Hub for Transforming the Mining Value Chain (TMVC), University of Tasmania, Tasmania, Australia

Alunite and aluminum phosphate-sulfate (APS) are diagnostic advanced argillic alteration minerals in lithocaps – both belong to the alunite supergroup. A notable distinction between alunite and APS is that the former is a sulfate endmember, whereas the latter encompasses phosphate, arsenate, or mixture of sulfate-phosphate-arsenate of the alunite supergroup. Much attention has been paid to alunite ([K,Na]Al$_3$(SO$_4$)$_2$OH$_6$) after the recognition of its usefulness as a heat source proximitor in lithocaps. In contrast, little is known about the significance of APS minerals in porphyry-epithermal deposits, despite their common occurrence within the core of alunite.

The results from our recent studies at porphyry-epithermal deposits and prospects (e.g. Buckskin lithocap – Yerington district, Nevada, and Resolution porphyry Cu-Mo deposit in the USA, Pascua-Lama high-sulfidation deposit in Chile and Argentina, Cerro Casale porphyry Cu-Au deposit in Chile, La Zanja high-sulfidation deposit in Peru, Lepanto high-sulfidation deposit in the Philippines, and Tujuh Bukit porphyry – high-sulfidation deposit in Indonesia) reveal that APS minerals are far more abundant than previously thought, especially in large porphyry and epithermal deposits. They not only occur in the advanced argillic alteration zone in the epithermal environment but also in the phyllic alteration zone in the porphyry environment, with a systematic vertical variation in textures, mineral associations, and chemical compositions. Such significant vertical distribution and variation spanning from the porphyry environment to the epithermal environment make APS minerals ideal candidates to study the formation processes of porphyry-epithermal deposits and they have great potential to be used as an indicator mineral of alteration environment, and also for developing bathymeters (the vertical equivalent of a proximitor), and for fertility discriminators during mineral exploration.
Contribution of remote sensing and geophysics to the exploration of a gold site: case of Iskel occurrences (Western Hoggar, Saharan desert), preliminary results

Neila Seray, Hadj Ghani Menasria, Abderaouf Lateche, Ismahane Chaouche
University of Sciences and Technology Houari Boumediene, Department of Geology, Algeria

Known for the presence of a high density of gold mineralization, the Hoggar shield is a favourable area for gold prospecting. The Silet (old Iskel) terrane, part of the central branch of the western Hoggar, contains several orogenic gold deposits. The terrane is elongated from North to South and limited by two major shear-zones: the East side shear zone forms the border that follows the 4°50’ line of longitude and the Iskel shear zone forms the west side border which follows the 4°30’ line of longitude.

This study is based on the Idereksi, Seldrar and Assouf Mellene gold occurrences and aims to highlight the main controls of these gold-mineralized locations and to detect the spatial relationship between auriferous quartz lodes, structures and geological formations. The major objective is to develop a reliable prospecting guide based on the main methods used in geophysics and remote sensing. These are the analysis of aeromagnetic and aero-spectrometry maps and satellite image processing by delineating the area most likely to concentrate gold and using various thematic maps developed in our study.

It emerges that auriferous quartz lodes have a spatial relationship with ultramafic, intermediate rocks and Taourirt granites. They are localized preferentially along secondary lineaments oriented N–S and NE–SW. The results obtained show that it is possible to optimize and refine litho-structural mapping and mining exploration in arid regions, in addition to conventional methods by visual interpretation of images and thematic maps from remote sensing and geophysical data.
Stratigraphy, hydrothermal alteration and geochemical signature of Faina gold deposit, Pitangui Greenstone Belt, Brazil

Gabriel Machado da Silva, Atlas Vasconcelos Corrêa Neto, Felipe Emerson Alves, Piero Azevedo Berquó de Sampaio
Federal University of Rio de Janeiro

Mariana Brando Soares
State University of Rio de Janeiro

Vitor Diniz Silveira
Jaguar Mining Inc.

The Faina gold deposit, like the nearby Turmalina Mine Complex, is hosted by the Archean Pitangui Greenstone belt at the northwestern sector of the Quadrilátero Ferrífero, Minas Gerais state, Brazil. A detailed macroscopic drill-core description was combined with multi-element geochemical analyses of 770 intervals of mineralized and non-mineralized rocks. The description of seven drill-cores allowed the separation of a saprolite interval (Supergene Zone – SZ) and an underlying primary Hypogene Zone (HZ). The HZ comprises a bottom domain which is composed of an intercalation of metasedimentary and metamafic rocks and a top domain composed of an intercalation of metamafic rocks. The main hydrothermal alterations are: white quartz-carbonate veins along the entire drill-core; sericitized veins; biotitization; and sulfidation, which is represented by syn-tectonic arsenopyrite, pyrite, pyrrhotite and chalcopyrite, and post-tectonic arsenopyrite, pyrite, pyrrhotite, chalcopyrite, sphalerite and stibnite. The first deformational phase (D_n) is marked by strongly foliated biotite, amphibole and a first generation of white quartz-carbonate veins, whereas the second (D_{n+1}) is evidenced by folded biotite and quartz-carbonate veins. A second generation of white quartz-carbonate veins crosscut the foliation. High-grade zones (>0.684 ppm Au) are distributed within the metamafic rocks, but are also present within the saprolite in the SZ. In the HZ, the mineralization is related to biotitization and dark-grey quartz-vein zones that crosscut the tectonic foliation (D_n). The quartz-veins at high-grade intervals display contrasting features to white quartz-carbonate veins such as the color, greater thickness and the presence of sulfide minerals filling fractures. Sulfide minerals recognized within the high-grade zone are arsenopyrite-pyrite-pyrrhotite-stibnite-chalcopyrite-sphalerite. Although high-detailed ore-petrography is paramount to identify the minerals that are related to the mineralization, identification of arsenopyrite, stibnite and biotite correlate with the overlapping anomalies of Au, As, S, Sb and K within the high-grade zones, which is also marked by anomalous W and Bi.
Precious metal transport and deposition is an intrinsic feature of hydrothermal activity in the Taupō Volcanic Zone (TVZ). Advances in the understanding of low-sulfidation epithermal ore-forming processes resulted from the drilling of deep wells for geothermal energy, in which information about fluid flow and mineral deposition under known pressure, temperature and fluid composition could be measured and quantified. For high-sulfidation environments, new knowledge was gained from studies of acid springs, crater lakes and fumarolic gases in active volcanoes. The ability to collect such data and then do a comparative analysis across several co-active hydrothermal systems showed how local and regional geological influences, especially those related to water-rock interaction and fluid flow, could be distinguished. Among the important findings, we have learned that: 1) deep hydrothermal fluids transport large amounts of gold and silver in geologically short periods of time; 2) ore-grade concentrations of precious metals accumulate by phase separation (boiling) and chemisorption in distinct parts of the epithermal environment; 3) the trace metal concentrations of deep hydrothermal fluids range widely with a large degree of intersystem variability despite a common geological context; 4) energetic two-phase fluid flow conditions in geothermal production wells are directly analogous to those producing low-sulfidation vein mineralization; 5) hydrothermal alteration and open-space infillings produce mineral-geochemical zonation in volcanic rocks that reflect the thermal and chemical structure of the epithermal environment and proximity to ore-grade mineralization; and 6) the strong difference in fluid chemistry producing acid alteration in high sulfidation environments in contrast to near neutral pH alteration in low sulfidation environments is directly related to the amount of water-rock interaction as a deep fluids rise. The TVZ has proven to be an unparalleled natural laboratory for resolving the spatial-temporal attributes of epithermal mineralization, and the resulting advances in understanding have strongly influenced development of current exploration models.
Hydrothermal minerals in epithermal deposits and geothermal systems, New Zealand: the connection

Mark P. Simpson
GNS Science, Wairakei Research Centre, Taupō, New Zealand

Low sulfidation epithermal deposits are the extinct analogy of geothermal systems and both share many of the same hydrothermal minerals. In geothermal systems, both alteration and open space deposited hydrothermal minerals can be directly linked with fluids of known temperature, pressure and composition and provide insight into how these same minerals formed in epithermal environments.

In geothermal systems of the Taupō Volcanic Zone and epithermal Au-Ag deposits in the Hauraki Goldfield, adularia, albite, illite, mixed layered illite-smectite, and smectite have zoned distributions. Adularia, that indirectly forms from boiling fluids, occurs in the central fluid upflow plume in geothermal systems and in epithermal systems it surrounds veins. Widespread illite, successively bordered by illite-smectite and marginal smectite, reflects temperature gradients with illite (≥220°C) formed under hotter conditions than cooler smectite (≤160°C). Epithermal veins mainly occur in adularia and illite altered rocks, but some can extend into illite-smectite altered rocks. Ammonium minerals (buddingtonite, tobelite) locally surround veins in a few epithermal deposits, but are rarely detected in geothermal systems. Conversely, geothermal systems commonly have volumetrically minor amounts of temperature sensitive mordenite (≤160°C), wairakite (≥220°C) and epidote (≥240°C), but these seldom occur in epithermal deposits probably because their hydrothermal fluid had high CO₂ concentrations that preclude their formation.

The key hydrothermal minerals that reveal the hydrologic structure of the hydrothermal system may be identified using analytical techniques. Illite, illite-smectite, smectite, and ammonium minerals can be rapidly identified using a field portable short-wave infrared (SWIR) reflectance spectrometer. Adularia can be identified using pXRD or inferred from potassium concentrations using pXRF. For epithermal systems, most quartz veins occur in rocks altered to adularia and illite, restricting the target area, although both minerals can occur >500 m from veins. Where present, ammonium minerals are localized to within <100 to 300 m from veins, reducing the target area.
Epithermal deposits of the Hauraki Goldfield, Aotearoa New Zealand

Mark P. Simpson
GNS Science, Wairakei Research Center, Taupō, New Zealand

Anthony B. Christie
GNS Science, Lower Hutt, New Zealand

Low (-intermediate) sulfidation epithermal Au-Ag vein deposits of the Hauraki Goldfield, have produced over 12.5 Moz of Au and 55 Moz of Ag since 1862. They are hosted in andesite-(dacite) and rhyolite, with 97% of Au recovered from veins in andesite. The quartz veins formed during the Miocene-Pliocene are up to 4.5 km in length, 25 m in width, and 700 m in depth. Alteration halos that encircle veins are 6–50 km² in areal extent, and the largest encompass several vein centers. The rocks are altered to quartz, adularia, illite, chlorite, pyrite, ± calcite. Adularia surrounds veins (100–500 m laterally) and is coextensive with illite that grades successively into illite-smectite and outlying smectite. Ammonium minerals, when present occur proximal to some veins (<100–300 m). Based on the geothermal analogy, adularia indicates zones of inferred high permeability and the upflow of boiling hydrothermal fluids. Illite, illite-smectite and smectite outline the broad thermal structure of the former hydrothermal system, with illite formed in the hotter portion. Epithermal veins are predominantly composed of quartz, ± minor adularia, ± clays (illite, corrensite, kaolinite) ± ± calcite/carbonates and ± pyrite. They display a diversity of textures including, banded (colloform and crustiform), massive, breccia, comb, and lattice-bladed; some with multiple generations of each. Electrum and acanthite are the main ore minerals with some deposits having Te- and Se-bearing minerals. Where present, chalcopyrite, sphalerite and galena occur in increasing amounts with depth. Gold is typically microscopic, but some deposits can have very high-grade electrum bands that have formed via the suppression of quartz deposition. The origin of bonanza-grade electrum at Thames and Coromandel remains enigmatic. The epithermal deposits can be broadly subdivided into northern, southern, and eastern groups based on their host rocks, age, Au/Ag ratios, and differences in vein minerals and textures.
Epithermal systems in the Bolnisi district, Georgia and the Artvin district, Turkey: fundamental features of alteration, ore-style and ore-forming patterns

Şafak Utku Sönmez, Robert Moritz, Titouan Golay, Stefano Gialli, François Turlin
Department of Earth Sciences, University of Geneva, Geneva, Switzerland

Jonathan Lavoie
IOS Services Géoscientifiques Inc. Saint-Paul, Chicoutimi, Quebec, Canada

Nino Popkhadze
Al. Janelidze Institute of Geology, Iv. Javakhishvili Tbilisi State University, Georgia

Malkhz Natvlishvili
Rich Metals Group, Tbilisi, Georgia

Ümit Aydın, Serdar Keskin
General Directorate of Mineral Research and Exploration of Turkey, Department of Mineral Research and Exploration, Ankara, Turkey

This study provides descriptive features of Late Cretaceous base metal and gold mineralization located in the Lesser Caucasus in Georgia and the Eastern Pontides in Turkey, which belong to a similar geodynamic setting. In this study, we compare the host rock, alteration and ore style characteristics of four main epithermal systems, including the Yanıklı prospect in Artvin district in Turkey, and the Beqtakari, Sakdrisi and Madneuli deposits in Bolnisi district in Georgia. The Late Cretaceous volcanic-volcaniclastic suites, hosting the deposits and prospects of the Bolnisi and Artvin districts are products of bimodal magmatism along the Eurasian margin, which is linked to the waning stages of the subduction of the northern branch of the Neotethys ocean. The composition of the volcanic host rocks is predominantly rhyolitic to dacitic, with subsidiary intermediate to mafic compositions in each district. Argillic alteration (Yanıklı, Beqtakari, Sakdrisi), propylitic alteration (Yanıklı, Beqtakari, Sakdrisi and Madneuli), phyllic alteration (Yanıklı, Sakdrisi, Madneuli) and intense silicification (Beqtakari) are the main alteration types present in the Bolnisi and Artvin districts. The predominant alteration minerals include chlorite, sericite and kaolinite group minerals. Gold ore bodies occur at shallow depth, whereas Cu-rich ore bodies with subsidiary Pb and Zn mineralized zones occur at deeper levels in Yanıklı and Beqtakari. Sakdrisi consists of a deep stockwork of multistage banded Au-Cu-bearing quartz-carbonate veins (Sak-IV) and a stockwork of quartz-poor massive chalcopyrite and pyrite veins. Madneuli consists of a sub-vertical stockwork part with mainly pyrite and chalcopyrite, and a sub-vertical pyrite-chlorite-hematite-telluride±chalcopyrite gold vein system. Considering the lithology, alteration and ore-style characteristics of each deposit and prospect, we conclude that they can be interpreted as belonging to the same regional Late Cretaceous ore-forming event. Further studies are needed to understand if they were produced by similar ore-forming fluids derived from similar sources.
Tracking the Ernest Henry signature: insights from epidote and chlorite chemistry

Jeffrey A. Steadman
CODES (Centre for Ore Deposit and Earth Sciences), University of Tasmania, Sandy Bay, Tasmania, Australia

Trace element chemistry of hydrothermal alteration minerals is becoming a standard tool in mineral exploration for many types of ore systems. This laser ablation ICP-MS based technique enables the identification of subtle geochemical variations that may be undetected by other methods, such as whole-rock X-ray fluorescence (XRF) and portable XRF. The trace element characteristics of chlorite- and epidote-group minerals have been utilized successfully for over a decade in porphyry exploration, but their applicability to other ore systems has not been well tested. Samples of epidote- and chlorite-altered metavolcanic rocks from the Ernest Henry copper-gold deposit, Cloncurry district, NW Queensland, were analyzed for their trace element contents and deportment. Epidote from Ernest Henry is enriched in several trace elements, including As (>500 ppm), Sb (>100 ppm), V (>1,000 ppm), Bi (>20 ppm) and Mn (>1 wt. %). Chlorite from Ernest Henry is low in Zn (<1,000 ppm) and Sr (<100 ppm) but contains high Mn (>1 wt. %) and Ni (≤3,000 ppm). The chemistry of both minerals correlates well with distance from the ore body – for example, epidote from within the ore zone contains lower As than epidote from outside the ore zone, and the amount of As in epidote increases with distance from the deposit. Furthermore, the Ti/Sr ratio in chlorite (an indicator of fluid temperature in porphyry systems) shows over three orders-of-magnitude variation that correlate with distance from Ernest Henry. These results indicate that mineral trace element chemistry techniques may be used to track the hydrothermal fluid signal in IOCG systems.

Controls on Fe-Ti oxide formation in the Cloncurry district, Mt. Isa Inlier, NW Queensland: insights from Ernest Henry and Starra 222

Jeffrey A. Steadman, Max Hohl
CODES (Centre for Ore Deposit and Earth Sciences), University of Tasmania, Sandy Bay, Tasmania, Australia

Iron-Ti oxides are ubiquitous in metavolcanic and metasedimentary rocks of the Cloncurry district, NW Queensland. The most common oxides are magnetite, ilmenite and hematite, but others are also present. We examined samples from two Cu-Au deposits (Ernest Henry and Starra 222) to document their Fe-Ti oxide mineral petrography. High-Ti magnetite (titanomagnetite) is recognized by the common presence of ilmenite exsolution, either as ‘trellis’ lamellae parallel to the 111 crystallographic axes, as ‘sandwich’ lamellae interlayered with magnetite, or a combination of both. In contrast, low-Ti magnetite lacks these features but does exhibit oscillatory chemical zonation, as well as common nano-inclusions of W-rich phases (i.e. scheelite or wolframite). Apart from its typical association with standalone titanomagnetite, ilmenite commonly hosts titanomagnetite-rutile symplectites that appear together with nano-scale hematite exsolution lamellae. In many areas, these ilmenite grains have been partially to completely replaced by titanite during either late-stage magmatic oxidation or early high-temperature hydrothermal alteration. Standalone hematite is typically present as incipient to near-total replacements of low-Ti magnetite grains, especially along fractures and grain boundaries in the latter (i.e. martite). On the other hand, coarse-grained specular hematite is abundant in the upper zones of the Starra 222 deposit. Rutile at Ernest Henry is typified by complex oscillatory and sector zonation, with W substitution for Ti being the cause of most of the observed zonation. These data provide important information regarding the long-lived and multistage growth histories of Fe-Ti oxides and related minerals in both Ernest Henry and Starra 222 and underscore the need for thorough petrographic characterization of these mineral phases across the Cloncurry district and other IOCG terranes.
Halogen and sulfur evolution from apatite in porphyry-like volcanic systems, West Luzon Arc, Philippines

George Stonadge, Andrew Miles, Tom Knott, Daniel Smith
School of Geography Geology and the Environment, University of Leicester, Leicester, United Kingdom

Simon Large
Department of Earth Sciences, Natural History Museum, Cromwell Road, London, United Kingdom

Chlorine and sulfur play key roles in the transport and precipitation of metals in porphyry copper systems (PCS). Tracking the evolution of such elements in trans-crustal arc systems is difficult due to their mobility and tendency to rapidly re-equilibrate with hydrothermal fluids and/or late stage melts. A significant problem is how the intermediate to evolved magmas - commonly associated with PCS - become enriched in S, and how Cl-rich fluids evolve during PCS formation.

Analysis of phenocryst-hosted apatite from volcanic deposits at Pinatubo show a progressive decrease in XCl/XOH and increases in XF/XCl through time. These shifts are coincident with a rise in S (from 0.1 to 0.75 wt.%). This shift reflects an increase in XF and relatively small decrease in XCl. Fluorine has a significantly lower fluid-melt partition coefficient than Cl and thus we interpret the increases in this ratio to be a result of volatile saturation. Fluid saturation appears also to trigger the oxidation of the melt, and dissolution of sulfides, thereby causing the concurrent increase in S. Pinatubo shares many similar characteristics with nearby PCS, including high Sr/Y ratios, depletion in mid-rare earths and S rich eruptions.

A second volcanic system, Taal, has no evidence of Cu mineralization. Here, phenocryst-hosted apatite have similar XCl, low S (< 0.1 wt.%) and exhibit minor changes in XOH and XF over time. The absence of Cu mineralization at Taal may be due to a lack of volatile saturation with no evidence of any coincident rise in S.

These results will be compared with zircon hosted apatite from the Santo Tomas II and Sanguillo porphyry copper deposits. The findings have broad application to understanding the volatile evolution of PCS both in the West Luzon Arc and worldwide.
Generating multiscale, multivariate geology logs from hyperspectral outputs

Jessica Stromberg, June Hill
CSIRO Mineral Resources, Kensington, Western Australia, Australia

Hyperspectral tools provide fast, field-friendly, and cost-effective methods to extract mineralogical data from drill core. As such, modern exploration and orebody characterization workflows are increasingly including the collection of large hyperspectral data sets to support geological logging and ore deposit modeling. Recent years have also seen rapid advancements in instrumentation, data processing, and data integration methods, which have expanded the available spectral range and subsequent applications of hyperspectral methods. However, given the inherently qualitative nature of hyperspectral outputs unless calibrated with other methods, the generation of geologically meaningful and objective multivariate outputs which can be used for geological modeling or logging is challenging. Here we show how common, conventionally derived, qualitative hyperspectral outputs from drill core such as spectral mineralogy/contribution and spectral indices/scalars from the VNIR-SWIR and TIR spectral ranges can be used to generate intuitive, objective, and geologically meaningful geology logs of alteration and lithology. Using examples from publicly available Australian geoscience datasets from Cu and Au deposits and exploration targets, we show that these logs are complementary to both traditional logging methods and geochemically derived logs, and that the outputs are intuitive as the domains (units) are described by hyperspectral mineralogical proxies, which geologists can easily relate to rock type and alteration assemblages. We also show that hyperspectral outputs can be integrated and visualized with other geoscience datasets collected at the same scale, including geochemical data. This is done using machine learning, statistical, and signal processing techniques which incorporate spatial information and domain geoscience knowledge into the interpretation process using the CSIRO-developed Data Mosaic software. The resulting multiscale and multivariate interpretation and visualization of hyperspectral outputs as geological or alteration logs can be used to support and complement traditional logging methods and be imported directly into geological modeling software.
Controls on high-grade versus refractory mineralization in Archean orogenic gold systems

Sumail, Nicolas Thébaud, Quentin Masurel, Laura Petrella
Centre for Exploration Targeting, University of Western Australia, Crawley, Western Australia, Australia

Although orogenic gold deposits form one unified class, individual deposits vary significantly in their mineral paragenesis, associated deformation styles and the resulting gold grades. Understanding the processes that control the variation in gold grades has significant implications for the predictive targeting of high-grade mineralization. In this study, we compare the ore mineral assemblages and the structural framework of two spatially and temporally coeval gold deposits with remarkably contrasting gold grades in the world-class Jundee-Bogada system of the Yilgarn Craton in Western Australia.

The Jundee and Bogada gold deposits present a comparable structural architecture and lithological association. The two deposits, however, differ mainly in the nature of their ore which results in contrasting grades. At Jundee, mineralization is associated with anomalously high-grade free gold (up to 1% Au) intercepts, whereas, gold mineralization at Bogada, is dominantly present as sulfide-hosted refractory ore (intercepts up to 0.05% Au). Ore lodes for both deposits are hosted in mafic rocks by strata-parallel shear zones. Yet, ore textures and associated structural elements at Jundee point towards brittle conditions compared to ductile at Bogada. Furthermore, paragenetic assemblages characterized by calcite ± quartz ± sericite ± chlorite ± pyrite ± arsenian pyrite ± arsenopyrite are suggestive of low-temperature assemblages at Jundee. On the contrary, lode alteration at Bogada is represented by narrow haloes of biotite ± albite ± calcite along with disseminated pyrite, arsenopyrite, pyrrhotite and minor chalcopyrite. The presence of biotite as the principle potassium-bearing mineral is typical of orogenic gold deposits formed under upper greenschist to lower amphibolite conditions, suggesting that Bogada gold mineralization formed under higher P-T conditions compared to Jundee. Based on our comparative study, we propose that different P-T conditions combined with selective structural traps likely resulted in bonanza gold at Jundee compared to lower-grade refractory gold at Bogada.

The geodynamic controls on modern seafloor massive sulfide deposition: a remote-predictive mapping approach

David Summer, Melissa Anderson
Department of Earth Sciences, University of Toronto, Toronto, Ontario, Canada

Seafloor massive sulfides (SMS) are the modern analog to ancient volcanogenic seafloor massive sulfides (VMS) found on land in ancient terranes. Discovering the tectonomagmatic controls on the evolution of SMS deposits will help to inform on marine mineral exploration as well as help to reveal the genesis of ancient systems. The Solomon-Vanuatu Arc/Backarc is a unique, living laboratory in which complex geodynamic processes over the past 10 Ma have dictated active volcanism and hydrothermal venting. As on land, geologic and structural maps are essential tools for evaluating the interplay between these systems. To date, marine geologic maps have poor resolutions relative to their terrestrial counterparts due to inaccessibility of the seafloor. The purpose of this study, therefore, is to produce a 1:1,000,000 lithotectonic map of the region via the integration of the breadth of available geophysical data and the development of a novel remote-predictive mapping approach. The data compilation includes high resolution ship-track bathymetry, satellite altimetry, magnetic anomaly, gravity anomaly and vertical gravity gradient data. Geomorphic and structural classification is accomplished via visualization and manipulation of the data in an ArcGIS workflow. Discrete changes in the regional stress regime and the resulting changes in patterns of volcanism are interpreted from crosscutting and superposition relationships of the mapped features. Geodynamics of currently active zones is assessed by examining surficial structures in relation to shallow earthquake focal mechanism data. This study aims to produce the most comprehensive synthesis of the tectonic, volcanic and hydrothermal evolution of this area, providing new insights into the links between backarc rifting and the formation of economic mineral deposits.
Genesis of the Gongchangling BIF-related high-grade magnetite ore in the Anshan-Benxi area, North China Craton

Xiaohui Sun, Yan Luan
School of Earth Science and Resources, Chang’an University, Xi’an, China

The Precambrian banded iron formations (BIFs) are the principle source of iron for the global steel industry, and most of BIF-related deposits are high-grade hematite deposits. However, BIF-related high-grade magnetite ore represents a distinct type of iron mineralization. The Gongchangling iron deposit, located in the Anshan-Benxi area, northeast of the North China Craton, is hosted in the late Neoarchean Algoma-type BIFs. It is famous for the production of Paleoproterozoic BIF-related high-grade magnetite ore. Previous studies suggest that the genesis of high-grade magnetite ore was related to hydrothermal enrichment of BIFs with proponents for meteoric, migmatitic or metamorphic fluid.

The altered wall-rocks (enriched in garnet, actinolite and chlorite) of high-grade magnetite ores suggest that hydrothermal alteration occurred under neutral–alkaline conditions, consequently, the influence of acid meteoric fluid in the Paleoproterozoic on the formation of high-grade magnetite ore was relatively limited. Geochronological studies suggest that the age of migmatitic granite (ca. 2.5 Ga) was older than high-grade magnetite ore (ca. 1.85 Ga), thus the influence of migmatitic fluid is also excluded. Wall-rocks of iron ore-bodies (amphibolite and staurolite-garnet-biotite schist) recorded the amphibolite facies metamorphism, and garnet from the altered wall-rock of high-grade magnetite ore exhibits the growth zoning produced during prograde metamorphism. Therefore, it is suggested that genesis of the high-grade magnetite ore was related to metamorphic hydrothermal fluid related to the formation of the Jiao-Liao-Ji Belt. The metamorphic hydrothermal fluids flowed through BIFs along the weak tectonic zone dissolving silica to enrich the ore, and as a result, the reformed BIFs became high-grade magnetite ores.

The Agate Project

Nicolas Thébaud, Mark Jessell, Corinne Debat
The Agate Project, Perth, Western Australia, Australia

Luc Siebenaller
Le Soleil dans la Main, 48, Duerfstrooss L-9696 Winseler, Luxembourg

Starting in 2006, a team of researchers at the Institute de Recherche pour Le Développement (IRD) in Toulouse, France founded a research and capacity building network WAXI (the West African exploration initiative) including universities, geological surveys and the international mining industry with a focus on the tectonics and metallogenies of West Africa. In the first two stages of WAXI, the capacity building activities were led by the IRD. In WAXI stage 3, we established a partnership with “Le Soleil dans la Main” a Luxembourg-based NGO working in Burkina Faso. As the demand for training and research opportunities has much increased, the Agate Project was registered in 2020 as a charity based in Perth, Australia to maintain and further develop these training activities. The purpose of the Agate Project is to advance education by improving the quality of and access to professional training in the field of earth and planetary sciences with a focus on assisting African people. As such the Agate project offers a range of education opportunities for professionals, researchers and students based in Africa. In the first year of existence the Agate Project supported over 50 African post graduate students to participate to on-line short courses as well as delivered three short courses in both structural geology and structural geophysics dedicated to industry. The funds generated by the training courses help us to support African researchers and students in their research. In 2021, the Agate Project supported five Research scholarships for post graduate students enrolled in MSc and PhD studies as well as five postdoctoral research grants. The beneficiaries come from eight African nations, namely Mali, Ivory Coast, Senegal, South Africa, Algeria, Morocco, Togo and Ghana.
Magmatic stratigraphy of the Platreef at Tweefontein, northern limb of the Bushveld Complex

Erin S. Thompson, David A. Holwell
School of Geography, Geology and the Environment, University of Leicester, Leicester, United Kingdom

Andy Lloyd
Anglo American South Africa, Johannesburg, South Africa

The northern limb of the Bushveld Complex, South Africa, is globally renowned as one of the world’s largest resources of platinum-group elements (PGEs), with additional base metal mineralization. These metals are essential to the growth of sustainable and environmentally friendly technologies, particularly within the electric automotive industry, a market which is expected to grow exponentially in the coming decades.

The major PGE-Ni-Cu-Co deposit, known as the Platreef, is a high-grade unit at the top of the Critical Zone. It has PGE grades comparable with the Merensky Reef of the eastern and western limbs, typically 3-4 g/t (Pt + Pd + Rh + Au), but can increase up to 15 g/t, over a much greater thickness (tens of metres, rather than typically <1m in the Merensky Reef), along with substantially more associated Ni-Cu-Co in the form of magmatic sulfides. The Platreef has been suggested to be formed by discrete magmatic units or sills, each with their own metal budgets and thicknesses. Studies have used geochemistry, changing Ni:Cu and Pd:Pt ratios, mineralogy and platinum group mineral (PGM) assemblages to differentiate between these packages in the southern and central sectors of the limb.

This study uses downhole major and trace element geochemical data to identify and correlate discrete magmatic units at Tweefontein, in the central part of the Platreef. Although several units can be correlated between boreholes, variation is seen both along strike and down dip from the surface outcrop. The basement architecture, formed at Tweefontein by the Transvaal Supergroup, is shown to exhibit a control on the thicknesses and distribution of these Platreef units, alluding to the importance of fully understanding structural controls on grade distribution within layered intrusion deposits. Differing trace element geochemistry between several units also points to variation within the source magmas which form the Platreef at Tweefontein.
Monazite as an exploration tool for iron oxide-copper-gold mineralization

Caroline Tiddy, David Giles, Adrienne Brotodewo  
*Future Industries Institute, UniSA STEM, University of South Australia, Mawson Lakes, South Australia, Australia*  
*Mineral Exploration Cooperative Research Centre (MinEx CRC)*

Diana Zivak  
*Department of Earth Sciences, University of Adelaide, Adelaide, South Australia, Australia*

June Hill  
*CSIRO Mineral Resources, ARRC, Bentley, Western Australia, Australia*

Jim Hodgkison, Mitchell Neumann  
*OZ Minerals Limited, Adelaide, South Australia, Australia*

Resistate mineral phases (e.g. monazite) can preserve chemical compositions linked to mineralization events. These resistate phases can be distinguished from mineral phases in surrounding unmineralized basement rocks and that may have grown in association with other geological processes (e.g. metamorphism). In this study, we demonstrate that hydrothermal monazite related to iron oxide-copper-gold (IOCG) mineralization in the Prominent Hill and Carrapateena deposits in the Gawler Craton, South Australia, preserve chemical signatures that can be distinguished from other monazite in the region, including metamorphic monazite and monazite grown in association with shear zones. The chemical signature is characterized by elevated light rare earth element (LREE) values and depleted Y and Th concentrations. Monazite chemistry data was collected using an electron microprobe in thin sections to preserve the textural context of the monazite. We demonstrate that these chemical signatures occur in many IOCG deposits in the Gawler Craton. Hence, we propose that these chemical signatures can be applied as broad-scale criteria for IOCG exploration within the Gawler Craton.

The chemical signature of IOCG-related monazite is also seen in monazite hosted within younger cover sequence materials overlying the mineralized basement rocks at both the Prominent Hill and Carrapateena deposits. These observations demonstrate that the chemical signatures can survive weathering, erosion, transport and redeposition. Dispersion of monazite preserving the IOCG-related chemical signature within the cover sequence will effectively increase the geochemical footprint of mineralization.

The uniqueness of the IOCG-related monazite chemical signature in the Gawler Craton is further tested against the composition of monazite from regions outside the Gawler Craton. Preliminary results demonstrate that the chemistry of IOCG-related monazite within the Gawler Craton is not recognized elsewhere. However, we recognize that although monazite is present in IOCG deposits around the world, monazite chemistry data is lacking, therefore the comparative world-wide dataset is currently limited.
“Diversity is being invited to the party; inclusion is being asked to dance,”
Verna Myers (https://www.cleveland.com/business/2016/05/diversity_is_being_invited_to.html)

But what does inclusion mean? In the context of this study, it is: ‘A sense of belonging and ability to be one’s ‘whole-self’ at work, feeling respected and valued for who you are, feeling support and commitment from others so that you can do your best work’.

Inclusion is difficult to measure and cannot be easily assessed through surveys and data analysis or implemented by the actions of one person alone (e.g. compare with diversity that is easy to measure through metrics). Inclusion impacts on self-esteem, having a sense of worth or of being successful. If we feel included, we will likely be feeling respected and required, we will have high job satisfaction and a sense of achievement. Inclusion is arguably the most important factor in the Equity, Diversity and Inclusion (EDI) space.

We present results of an interview-based study of 68 geoscientists (40 women, 28 men) at various career stages and with roughly equal representation across academia, government and industry. Interviewees were asked to provide a visual metaphor (e.g. image, movie) describing their career and the career of the opposite gender. The metaphors and personal narratives provided were used to provide insight into geoscientists’ career perceptions. Given perceptions can shape how we approach our careers, gender differences in career perceptions may explain underlying reasons for gender inequality.

Our study shows that there is conflict between perceived agentic and communal behaviors within women and men geoscientists, that sense of achievement in Australian geoscientists is alarmingly lacking, and that women often feel like outsiders. We therefore ask how inclusive the geoscience community is and present a discussion on enablers and barriers towards fostering an inclusive community.
The state of Cu, Ag and In in sphalerite
determined by X-ray absorption spectroscopy of
synthetic crystals and theoretical modeling

Nikolay D. Trofimov, Maximilian S. Nickolsky, Olga N. Filimonova, Polina V. Evstigneeva, Boris R. Tagirov
Institute of Geology of Ore Deposits, Mineralogy, Petrography and Geochemistry, IGEM RAS, Moscow, Russia
Alexander L. Trigub
NRC “Kurchatov Institute”, Moscow, Russia
Dmitry A. Chareev
Institute of Experimental Mineralogy Russian Academy of Sciences (IEM RAS), Chernogolovka, Russia
Kristina O. Kvashnina
European Synchrotron Radiation Facility (ESRF), Grenoble, France

Sphalerite, ZnS, is a unique mineral that can host high concentrations of several “critical” elements that are in high
demand in the hi-tech industry. Among these is indium (In), a rare element in the Earth’s crust, that is rarely sufficiently
concentrated to form independent ore minerals, but is recovered as a by-product from refining of zinc concentrates. In
natural sphalerites, the concentration of In is directly correlated to the concentration of Cu. In this study we investigated
the substitution mechanisms in In-bearing sphalerite by X-ray absorption spectroscopy (XAS). For this purpose, we
synthesized sphalerite crystals in the systems Zn–In–S, Zn–Cu–S, Zn–Ag–S, Zn–In–Cu–S, and Zn–In–Ag–S, and
characterized the state of In, Cu and Ag by XAS, with emphasis on the extended X-ray absorption fine structure
(EXAFS). Furthermore, we characterized the distortion of the local atomic structure of sphalerite near In and Cu
admixture atoms by Density Functional Theory (DFT), theoretical modeling of X-ray Absorption Near Edge Structure
spectra (XANES), and Reverse Monte Carlo EXAFS fitting (RMC-EXAFS). Our results demonstrate that Cu and Ag,
in the presence of In, form a solid solution where the Me-S distances in the first coordination shell are correlated with
the ionic radii and increase in the order of Cu<Ag(<Au). The distortion of the atomic structure increases in the same
order. The distant (second and third) coordination shells of Cu and Ag in sphalerite are split into two subshells, and
the splitting is more pronounced for Ag. Since no heavy In atoms were detected in the 2nd shell of Cu by means of
EXAFS, and the 2nd shell of In was only slightly distorted, we conclude that the defects are distributed randomly (or at
least, not close to each other).
Accessory minerals: a window into Cu “fertility” in post-subduction magmas in the Aegean

Lauren Tuffield
British Geological Survey, Nicker Hill, Keyworth, NG12 5GG

Copper, and therefore its main host porphyry copper deposits (PCDs) are becoming an increasingly important resource in the transition to green electricity generation. Understanding the formation of PCDs is therefore more important than ever. PCDs are commonly found in subduction settings, however, PCDs are also found in smaller volumes within post-subduction settings, such as the Aegean. This latter group are much less commonly studied, remaining largely elusive due to their more isolated nature and lower volumes of mineralization. In order to find covered and less voluminous PCDs, a greater level of understanding of the processes and fingerprints that they leave behind is required.

The Aegean has a range of mid-Miocene to recent porphyry and epithermal deposits. The tectonic setting in which these deposits exist is well categorized, making this an ideal place to study the evolution of post-subduction magmatic-hydrothermal deposits, and their associated tectonic events. Compiled literature data shows that the post-subduction Aegean has a much more alkaline signature than the subduction environment of the South Aegean Volcanic Arc, along with a differing isotopic signature, indicating a more varied crust/mantle input in the Aegean.

Crystal clots have been observed in several samples from Lesvos, and their presence can indicate magma recharge, which is being investigated via pyroxene geochemistry. Pyroxene composition between crystal clots and phenocrysts differ appreciably in some samples, but less in others, with clots displaying a generally more Ca rich and Fe poor composition than phenocrysts. The significance of the crystal clots and their compositions to magmatic processes will be backed up by further collection of trace element data from zircon and other accessory minerals. Accessory minerals are especially useful because they provide information about discreet events leading up to PCD formation, in contrast with the average end view of numerous complex processes that whole rock geochemistry provides.
Textural characterization of the Fe-Ti oxides from the Tete Suite, Mozambique

David A.B. Unganai, Akira Imai, Kotaro Yonezu
Department of Earth Resources Engineering, Kyushu University, Fukuoka, Japan

Ryohei Takahashi, Andrea Agangi, Pearlyn Manalo
Department of Earth Resource Science, Akita University, Akita, Japan

Daud L. Jamal
Department of Geology, Eduardo Mondlane University, Maputo, Mozambique

Lewis D. Ashwal
School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa

The Tete Suite is an elongated and sub-horizontal sheet-like Mesoproterozoic intrusion covering a surface area of nearly 6000 km² in northwestern Mozambique. The suite is overlain by the Karoo Supergroup. Although its geology was extensively studied due to the occurrence of gold, copper and iron mineralization, no detailed study has focused on the origin and evolution of Fe-Ti oxides. We therefore characterized the Fe-Ti oxide textures of eleven samples of anorthosite, leucotroctolite, gabbro, and clino- and orthopyroxenite, with the aim of understanding the nature of the suite and associated oxide mineralizations.

The Fe-Ti oxides are predominantly composed of interstitial titanomagnetite and ilmenite (<5 vol.%), and their abundance varies with rock type. Anorthosite consists of ilmenite with minor titanomagnetite (<500 μm). Euhedral apatite (<20 μm) is spatially related to the Fe-Ti oxides, forming annealed textures. The oxides are also enclosed by amphibole. Gabbro is solely characterized by anhedral coarse grained titanomagnetite (>500 μm), occurring between lath-like plagioclase and clinopyroxene. Clinopyroxenite contains interstitial titanomagnetite (and minor ilmenite) and lenses of ilmenite (and minor titanomagnetite) associated with prismatic silicates, which is consistent with the layered nature of the intrusion.

Trace amounts of pyrite, chalcopyrite and pentlandite (<100 μm) are associated with the Fe-Ti oxides and some occur as inclusions in silicates in almost all samples.

Several microtextures suggest that the rocks underwent subsolidus processes during cooling. They include (1) lenticular hemo-ilmenite lamellae in ilmenite, whose abundance decreases towards the titanomagnetite-ilmenite boundary; (2) cloth-like lamellae of ilmenite associated with blebs and lamellae of spinel in titanomagnetite; (3) discrete grains of spinel along the titanomagnetite-ilmenite boundary; (4) symplectic intergrowths between the Fe-Ti oxides and orthopyroxene in leucotroctolite and orthopyroxenite; and (5) fine titanomagnetite-ilmenite lamellae along prismatic cleavages and diffused discrete oxides at the margins of clino- and orthopyroxene, suggesting crystallization from Fe-Ti rich magmas.
Characterizing the spatial distribution of regional and hydrothermal dolomitization along the Rathdowney trend, Ireland: implications for base metal exploration

Nicholas A. Vafeas, Murray Hitzman, John Güven, Koen Torremans

Irish Centre for Research in Applied Geosciences (iCRAG), University College Dublin, Ireland

The Irish Midlands is host to one of the world’s major zinc orefields and is the type locality of the so-called ‘Irish-type’ sulfide deposits. The emplacement of sulfide deposits along the Rathdowney Trend in the Irish Midlands is closely associated with the development of a dark, hydrothermally-derived dissolution breccia, locally referred to as the “Black Matrix Breccia” or BMB. Hydrothermal fluids, derived from interaction with basement rocks, migrated along relatively low displacement normal fault systems along the SW-NE oriented Rathdowney Trend. These fluids moved laterally outwards from the faults, along the contact between the lower Carboniferous Ballysteen formation (argillaceous bioclastic limestones) and the overlying Waulsortian Formation comprising largely micritic limestone derived from deep water carbonate mud mounds. The BMB formed through both dissolution and replacement of precursor limestone and regionally dolomitized limestone. This style of alteration resulted in the formation of a largely tabular dolostone body generally positioned along the base of the Waulsortian Limestone Formation, as well as lesser occurrences of tabular lenses developed several meters above the basal Waulsortian contact. This highly (micro)porous, cryptocrystalline dolostone forms a halo to the majority of Zn-Pb-(Fe) sulfide ore bodies along the Rathdowney Trend and is a key indicator for mineral exploration in the district. Examination of more than two thousand detailed drill logs, as well as available drill core from the Lisheen and Galmoy mines, indicates that zones of undolomitized, alteration-resistant precursor Waulsortian limestone are present within areas of BMB formation. The size and morphology of these undolomitized bodies are similar to those of original individual Waulsortian mud mounds in other portions of Ireland. This suggests that subtle variations in the original Waulsortian mud mound complex had a control on both regional and hydrothermal dolomitization and thus later base metal mineralization.
Mineral prospectivity of a lithium-bearing pegmatite, in northern Portugal

Julia Tucker Vasques, Alexandre Lima, Maria do Anjos Ribeiro

Department of Geosciences, Ambient and Spatial Planning, Faculty of Sciences, University of Porto, Porto, Portugal
Institute of Earth Sciences, ICT, Pole of University of Porto, Porto, Portugal

Environmental measures of the European Commission have resulted in an increasing demand for lithium and other critical materials. To meet this demand, new geological exploration technologies are required to discover and assess European critical material deposits. In this context, we have studied the Aldeia Pegmatite Li-Cs-Ta pegmatite veins located in the Barroso-Alvão pegmatitic field hosted by Silurian age mica-schist in northern Portugal. These vein deposits have an inferred and indicated resource of almost 45 tons of Li₂O.

In 2019, a drilling campaign was carried out on the Aldeia Pegmatite by Savannah Resources, comprising 26 reverse-circulation holes, 10 diamond-drill holes, and 6 reverse-circulation holes with diamond-drill tails. A total of 1430 m were analyzed in meter sections by ICP-MS at ALS laboratories.

This LCT type aplite-pegmatite is composed of veins up to 40 m long and 2 m wide. A petrographic study was undertaken assisted by portable XRF, demonstrating the use of this apparatus to identify cassiterite and manganese phosphates associated with the pegmatite wall-zone. Cathodoluminescence studies and SEM analyses were performed to identify the Li-pyroxene spodumene, the principal ore mineral of the deposit.

Spodumene was identified in a thin section at micrometer scale (~25 µm) within the shear-zone and contacts with the wall-rock, and centimeter scale (0.5 to 1.2 cm) in situ, on internal zones of the pegmatite body. A 3D-implicit model was constructed, aiming to classify the pegmatites facies with higher lithium grades associated with the centimeter sized spodumene.

Geochemical patterns were analyzed along with the facies classification and model construction, demonstrating that the higher lithium grades are in the internal zone of the pegmatite. An increase in Sn concentration towards the northeastern part of the deposit can be related to the shear-zone. There are low concentrations of other critical materials such as cesium and tantalum.

Antimony mineralization: the Archaean Murchison Belt, South Africa

Julian R. Vearncombe
Retired, Auckland, New Zealand

The ENE-trending Murchison Lineament in northern South Africa is one of the world’s most important structures for its control on world-class mineral deposits, Proterozoic sedimentary basins, and giant igneous intrusions. The deepest exposed Archaean parts of the lineament are the Murchison Belt. Despite being implicated as a source of gold for the world’s largest natural accumulation of gold in the Witwatersrand Basin, the absolute age of Sb-Au mineralization in the Murchison Belt is poorly constrained. SHRIMP U-Pb geochronology was used to date monazites from a Sb-Au ore sample from the granite-hosted Malati Pump orebody and determine ages for two different generations of monazite, both associated with ore minerals. The older age of 2832±23 Ma is from a minority of grains and is interpreted to date the primary Sb-Au mineralization, about 100 Ma after belt formation. This age predates, or is possibly synchronous with, the upper-Witwatersrand gold-bearing Central Rand Group. The younger age of 1968±17 Ma from a majority of monazite grains is unrelated in time to known events and interpreted here as a cryptic hydrothermal reworking of the Sb-Au ores in this deposit, possibly related to Proterozoic dolerite dyke intrusion. Rutile U-Pb geochronology on the same ore sample produced equivocal results due to very low U-contents but is weakly supportive of rutile formation at ~2832 Ma and overprint during the ~1968 Ma event.
Function and status of structural geology in resource management

Julian R Vearncombe
Retired, Auckland, New Zealand

Basic, nuts and bolts structural geology is the unheralded success story central to brownfields exploration that in Australia, and globally, has grown many-fold mineral deposits beyond the start-of-mine reserve. Highlighting the epistemology that informs management, this presentation is aimed at practitioners and managers in industry and at academics wishing to benchmark structural geology.

Structural geology applied to resources has changed recently beyond recognition. Now, structural geology is practiced daily and in-house by most exploration and mining companies. The days of the amazing one-off report by a consultant are over. The value-add performed by a minerals company is the systematic building and communication of a 3D picture of the basic structural geology, and rarely are academic models, although these models encourage critical thinking and communication. Computer modeling in 3D has come of age, as essential structural data are integrated with other data and combined with embedded knowledge. It is detail that makes for discoveries and mine extensions.

Whilst structural geology is the unheralded success of brownfields exploration, it remains under-utilized in resource evaluation. Consultancies, software developers, and academics are all needed to apply structure to (1) better define ore zone margins and (2) distribute grade, as well as contaminants when necessary, across mining blocks between widely spaced sample data from drill holes. Workflows, hierarchy charts, and similar boxing of structural geologists and their tasks are counterproductive. Every and any geology student may be destined to be a stakhanovite, hence they need a comprehensive and solid background in structural geology with field experience. Structure is too important to be left to end of degree electives.

Coupling Disc-Based Association and Random Forest for prospectivity mapping

Alex Vella, Guillaume Bertrand, Bruno Tourlière, Eric Gloaguen, Vincent Labbé
Bureau de Recherches Géologiques et Minières (BRGM) – Orléans, France

Charles Gumiaux, Stanislas Sizaret
Institut des Sciences de la Terre d'Orléans (ISTO – UMR 7327) – Orléans – France

From a general point of view, prospectivity mapping aims at outlining areas with the highest likelihood to host mineralization. In this frame, data-driven approaches rely on statistical and spatial analysis applied on diverse geological features and known mineral occurrences to estimate likelihood, while minimizing the expert inputs in the model. As such, we present here the new “Disc-Based Association” (DBA) method – a prospectivity tool derived from the “Cell-Based Association” (CBA) method – used to pre-process the data. While most predictive models rely on searching for associations between mineralization and specific geological formations, this method aims at overcoming precision and positioning problems related to geological maps by considering geological environments. The study area is discretized in a regular node grid. Different information layers can be thus integrated (e.g. lithological and structural features, geochemical or geophysical data) and the associations of all these geological factors is defined around each node. Pre-processing of map data thus results in a multivariate matrix covering the study area. Finally, a Random Forest predictive model computes the score from this matrix, allowing it to (i) highlight specific associations around mineral deposits, (ii) define one or several metallocenthes for the considered commodity and then (iii) produce favorability maps. This new methodology is here applied to prospectivity mapping of Sb throughout the West European Variscan Ranges at multiple scales along the Ibero-Armorican Arc. This allows testing and evaluating its consistency for a multi-scale approach. Its efficiency is compared to other methods already used with CBA. We infer that this new multiscale and multidomains data-driven approach coupling DBA and Random Forest will improve this prospectivity mapping method while giving new insights on the genetic processes resulting in Sb deposits through the Variscan Range.
Metallogeny of Sb along the Ibero-Armoricanc Arc: insight from data-driven prospectivity mapping

Alex Vella, Guillaume Bertrand, Bruno Toulliére, Eric Gloaguen, Vincent Labbé
Bureau de Recherches Géologiques et Minières (BRGM), Orléans, France

Charles Gumiaux, Stanislas Sizaret
Institut des Sciences de la Terre d'Orléans (ISTO – UMR 7327), Orléans, France

The ERA-MIN2 AUREOLE (ANR-19-MIN2-0002, https://aureole.brgm.fr) project, funding this PhD research work, aims at better understanding controls of Sb deposits during the Variscan orogeny. In that frame, this work is based on the analysis of Sb prospectivity maps computed throughout the Ibero-Armoricanc arc (West European Variscan Range) to outline areas with the highest likelihood to host mineralization, at multiple scales. Based on a data-driven approach, the methodology we developed also allows (i) quantifying the specific and systematic associations between deposits and geological features, and (ii) distinguishing several possible metallotects at the origin of Sb deposits in the study area, which are compared to the metallogenic models traditionally proposed for Sb deposits. We infer this new multiscale and multidomains data-driven study will help understanding metallogenic processes controlling Sb concentrations within the Variscan crust. In particular, recent results from the Armorican Massif show that Sb deposits must result from at least two distinct metallogenic events during early and late collisional phase; our study allows testing this at diverse scales and for diverse domains through the Ibero-Armoricanc Arc. The use of a data-driven approach implies heavy reliance on statistical and spatial analysis applied on geological features and known mineral occurrences – while minimizing as much as possible the expert inputs in the model – to determine the likelihood of hosting Sb mineralization. Most predictive models rely on finding associations between mineralization and specific geological formations, despite the problems related to geological maps, such as the precision of the geological features displayed or the presence of superficial formations. To overcome these problems, we develop here the “Disc-Based Association” (DBA) method to identify geological environments by discretizing the study area in a regular node grid. A Random Forest approach is then applied to recognize systematic and specific associations between map features and known Sb deposits.

Multivariate geochemical analysis applied to mineral exploration in the Andean-type tectonic setting

Ángel Verbel Olarte, Maria Emilia Schutesky
Universidade de Brasília

Daniel D. Gregory
University of Toronto

The Andean tectonic setting is comprised of a mountain chain of over 8000 km long and up to 800 km wide at its thickest part, which has undergone a complex variety of processes to develop its present geology. Since many of these mechanisms are still active, it makes it an outstanding case study to evaluate the formation of ore deposits in this tectonic setting. Many of the most important mineral accumulations are related to magmatic arcs and are genetically related to magmatic-hydrothermal processes associated with plate subduction. The development path that the rocks and mineral deposits have followed over time is reflected in their geochemistry, with variations introduced as a result of the different geological and structural settings and processes experienced over time. Principal components analysis (PCA) of a large number of random geochemical samples in the Andes from the GEOROC database made it possible to establish a dimensional reduction, showing differences between samples from areas with high fertility, ore deposits, and barren areas. This resulted in a map that shows prospective areas for greenfield exploration as well as laying the foundations for more detailed works in brownfield exploration.
Magmatic, hydrothermal and weathering processes play important roles in the enrichment of REEs in carbonatites but identifying the relationship between these processes and REE mineralization can be challenging. Stable isotopic systems of carbon, oxygen and sulfur aid in constraining the origin of the REE mineralization in carbonatites because carbonatites contain carbonate, sulfide and sulfate minerals that form throughout most of the paragenesis and tend to occur with REE mineralization. We utilized this approach to constrain the origin of the REE mineralization of the Elk Creek carbonatite (Nebraska, United States), a multilithologic carbonatite with ore-grade enrichment primarily associated with a late-stage barite dolomite carbonatite unit. Magmatic and hydrothermal dolomite have been identified based on textural and chemical variations. The C-O isotopic values of early, magmatic dolomite, $\delta^{13}C = -4.4$ to $-3.3\%$ and $\delta^{18}O = +8.8$ to $+9.2\%$, plot within the primary igneous carbonate field, and the hydrothermal dolomites have heavier C and O isotopic compositions, up to $-1.2\% \delta^{13}C$ and $23.0\% \delta^{18}O$. Modeling of the C-O isotopic data reveals that some of the isotopic variation could have resulted from closed system Rayleigh fractionation of an evolving carbonatitic magma between 300 and 500°C, but excursions to heavier $\delta^{18}O$ is likely the result of interaction with $H_2O-CO_2$-fluids at temperatures between 400 to 100°C. The $\delta^{34}S$ of pyrite varies from $-16$ to $0\%$ consistent with magmatic and hydrothermal origins. The pyrite with heavier values is primarily associated with magmatic dolomite. The $\delta^{34}S$ of barite varies from $-7$ to $+13\%$, consistent with hypogene and supergene origins. Stable isotopes suggest that the REE mineralization was primarily hydrothermal in origin with fluids derived from both the carbonatite and country rock. Supergene processes may have also contributed to REE enrichment in parts of the complex.
Inheritance of trans-lithospheric structures and fossil ore-fertile mantle source domains at long-lived supercontinent margins

Daniel Wiemer, Steffen G. Hagemann, Anthony I.S. Kemp, Nicolas Thébaud, Laure Martin, Jon Hronsky

Center for Exploration Targeting, University of Western Australia, Crawley, Western Australia, Australia

Trevor Ireland

Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia

Carlos Villanes

Compañía Minera Poderosa S.A., Lima, Perú

The repeated accretion-convergence and extension at supercontinent margins can be regarded as a factory for the formation of world-class copper, gold and associated base metal ore deposits of various type and style. Each successive episode of subduction supplies metal and volatile budget, tapped by hydrous partial melting of the metasomatized sub-arc mantle wedge. Simultaneously, the extraction of melt during continued influx of subduction-slab derived volatiles and metals, leaves behind a refractory, but enriched sub-continental lithospheric mantle keel (SCLM). Both the fertile mantle wedge and the enriched SCLM may be subject to sourcing of melt/fluid feeding crustal ore-deposits during subsequent tectono-thermal events, provided that trans-lithospheric permeability is maintained or activated.

Here, we present a multi-methodological study of part of the north Peruvian Eastern Andean Cordillera of South America to shed light on the inheritance of pre-Andean trans-lithospheric structures and fertile mantle source domains to explain both the spatial distribution and the source for major ore deposit clusters in the Andes. We identify a so far unrecognized Paleozoic suture between Gondwana and a marginal ribbon of micro-terranes that cuts through the Andes at an oblique strike angle. Major Paleozoic to Miocene ore deposits cluster along this suture and/or its inherited cryptic extension transecting the Andean belt. At the intersection of the inherited structure and the Andes, lies the world-class Carboniferous Pataz-Parcoy intrusion-related orogenic gold vein system, which displays a hydrothermal architecture that was controlled by the structural inheritance.

Our regional-scale fieldwork, bulk-geochemical and in-situ U-Pb-Hf-O zircon analytical data from Carboniferous magmatic rocks that are host to the Pataz-Parcoy system allow for an in-depth view on the metallogenic potential of the area. We show that both the time-integrated evolution of the Carboniferous arc, and the inheritance of structural magma/fluid pathways and fertile mantle domains played a critical role in the formation of ore deposits.
Mineral systems model for surficial uranium deposits

Andy Wilde
Centre for Exploration Targeting, University of Western Australia, and Elevate Uranium Ltd

Growing demand for green energy is manifested in a large number of nuclear reactors under construction and planned. This increase in global nuclear capacity will require discovery of additional uranium resources to meet increased demand for and falling supply of uranium. In this paper I review the so-called “calcrete” or “surficial” type of uranium deposit, numerous examples of which occur on many continents. Key features of the deposits are explained in the context of a mineral systems approach, but as with many types of uranium deposit, research has been negligible in recent years, reflecting past oversupply of uranium. Consequently, many questions remain as to descriptive details and the genesis of this important group of deposits.

Potentially economic deposits occur either in current drainage or in shallow (< 50 m) palaeodrainages in relatively arid areas such as Western Australia’s desert regions, the Namib Desert of Namibia, the Patagonia deserts of Southern Argentina and many others. The source of uranium is likely to have been granitic (sil) rocks that are traversed by these drainages, although few if any studies have explicitly addressed the question of source and how uranium is transplanted from source to sink. The depositional process of uranium (principally as the vanadates carnotite and tyuyamunite) remains poorly understood but is generally assumed to involve transport of aqueous uranium species as opposed to deposition of detrital uranium-bearing heavy minerals with localized solution and redeposition of uranium. Possible depositional mechanisms include mixing of discrete U- and V-rich groundwaters, evaporation and/or interaction of uraniferous groundwater with pedogenic carbonate (by changing groundwater pH). There are few absolute age determinations for any of the deposits, but no deposits occur in rocks older than Tertiary. This reflects low preservation potential. For example, some Namibian palaeochannel-hosted deposits are deeply incised by active drainage with attendant erosion and removal of mineralized material.

Towards a mineral systems model for leucogranite-hosted uranium deposits

Andy Wilde
Centre for Exploration Targeting, University of Western Australia, and Elevate Uranium Ltd

Approximately 10% of annual uranium production comes from two low grade deposits in pegmatitic leucogranite intrusions at Rossing and Husab, located in Namibia’s Erongo region. This region also hosts most of the world’s undeveloped resources of this deposit type, amounting to in excess of 300,000 tonnes of potentially economically recoverable U3O8. Uraniferous leucogranite intrusions represent one of the last recorded events in a protracted history of felsic intrusion spanning the period 580 – 490 Ma. This voluminous intrusive event is attributed to the collision of the Congo and Kalahari cratons during the Pan-African (Damaran) orogenic event. Uraniferous intrusions postdate the main collision-related compressive deformation that is responsible for the overall architecture of the region. Approximately coeval with uranium are significant deposits of lithium, tin and gold. Some of the uranium is likely to have been introduced into the site of deposition in leucogranitic magma, as is evidenced by rounded inclusions of uraninite enclosed in magmatic feldspar. Nearly all primary magmatic uraninite has, however, been partially to completely altered to other phases and secondary (U6+) uranium phases comprise a significant portion of the mineralization at some deposits. The Damaran intrusions exhibit a range of bulk chemical composition, but it appears that the uraniferous intrusions tend to be somewhat more siliceous, with some examples being so rich in silica that the term “quartzolite” can be applied. Quartz-rich portions of the pegmatitic leucogranites typically have the highest uranium grades, with the quartz being characteristically gray or black. In some instances, black quartz forms discontinuous veins, supporting the hypothesis that some uranium was introduced in (or redistributed by) hydrothermal fluid. Alteration of primary magmatic uraninite could also be due to recent dissolution and transport of uranium related to formation of secondary palaeochannel-hosted deposits.
Source rocks for metals in basalt-hosted
VMS deposits: Semail ophiolite, Oman

Robin C. Wolf, Larryn W. Diamond, Thomas Pettke
Institute of Geological Sciences, University of Bern, Bern, Switzerland

Thomas M. Belgrano
School of Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, UK

Volcanogenic massive sulfide (VMS) deposits in mafic terranes are valuable sources of Cu and Zn and other minor metals. Whereas their formation at seafloor black-smoker vents is well established, the source rocks of their metals are still debated. Proposals include the vast volumes of footwall basalts hydrothermally altered to spilite (chlore+albite+quartz±actinolite), the smaller bodies of epidote alteration (epidote+quartz+titanite+Fe-oxides) in the upper crust, and magmatic volatiles liberated by oceanic plagiogranites. Recent fluid inclusion studies and geochemical modeling in the Semail ophiolite favour the regionally distributed spilites as sources of the 0.9 Mt Cu in the ~20 known VMS deposits. Our ongoing study aims to test the spilite source-rock hypothesis by analyzing rocks throughout the upper crust of the Semail ophiolite. Samples along a transect near the Safwa VMS deposit were collected from the base of the Sheeted Dyke Complex up through the comagmatic MORB-type ‘Geotimes’ lavas, both of which represent products of spreading-axis magmatism, as well as through the overlying post-axial ‘Tholeiitic Alley’ and ‘Boninitic Alley’ lavas. Copper concentrations are 1–50 µg/g in the axial lavas and 1–140 µg/g in the post-axial lavas. Zinc values show similar scattering, but a reversed stratigraphic trend: 10–110 µg/g in the axial lavas falling abruptly to 1–60 µg/g in the post-axial lavas. Possible controls on these distributions include variations in initial lava composition as a function of magma petrogenesis, variations in intensity of hydrothermal alteration, and hydrothermal additions of metals as secondary sulfides. The Semail upper crust is famous for its great thickness (>4 km in some places) and for its high intensity of alteration, including chlorite up to the top of the volcanic sequence. These factors may account for the greater variability in Cu and Zn values compared to the thinner and less intensely altered, in-situ oceanic crust.

Bayan Obo rare earth element deposit: revisiting the ore-forming process

Yuling Xie, Jiaming Xia, Pei Liang, Yunwei Qu
University of Science and Technology Beijing, Beijing, P.R. China

Bayan Obo, the world’s largest rare earth element (REE) deposit, is an important resource of light REEs, Fe and Nb. Since the initial discovery of Bayan Obo in 1927, varied hypotheses have been proposed for the origins of the host rock (H8 unit) including carbonatite emplacement, sedimentary carbonate processes, and hydrothermal replacement of sedimentary rock. Because of intensive post-ore deformation, metamorphism and hydrothermal alteration, the geological and geochemical characteristics of Bayan Obo is very complex which has resulted in the long-term controversy over the origin and enrichment mechanisms for REEs. Our new field observations, petrological, petrochemical and mineralogical results indicate that the host rock of the Fe-REE ore bodies is a carbonatite-silicate complex including carbonatite and biotite which has been previously referred to as metasedimentary rocks or metavolcanic rocks of the lower Bayan Obo Group (H9 unit). The complex is composed of numerous parallel carbonatite-biotite dikes emplaced by successive magma pulses. Each dike comprises an outer biotite-rich zone and an inner carbonate-rich zone. The mineral zonation of the complex is similar to the symmetrical banded structure in normal hydrothermal veins. From early (north) to late (south) dikes, the carbonate-rich inner zones of the dikes show a gradual increase in fluorite, barite, magnetite and REE contents. The later stages of carbonatite have the highest contents of REE minerals and magnetite, hence almost all of the iron orebodies occur in the south wing of the H8 units. The mineral zonation of the complex and intrusive sequence of the carbonatite-biotite dikes record the magmatic evolution and provide evidence for the REE enrichment through magmatic differentiation. The magmatic evolution including the biotite and carbonate mineral fraction crystallization may play an important role for the REE enrichment in the final stage carbonatite.
Modeling deleterious elements with “less than one” datasets via deep learning methods and non-linear correlation studies

Farzi Yusufali  
Stratum, Toronto, Ontario, Canada

Ilia Sucholutsky  
University of Waterloo, Waterloo, Ontario, Canada

Creating resource models of secondary or deleterious elements despite inconsistent sampling or “less than one” datasets compared to the primary commodities (e.g. only 80% of all drillhole assays containing arsenic assays) is a valuable strategy for better mine planning and reducing operational risk. In this paper, we propose a machine learning (ML)-based protocol that accepts drillhole data from multiple elements simultaneously to produce grade predictions for a target secondary element. After initial linear and non-linear correlation analyses is conducted on all assayed elements against the target element, statistically significant non-linear correlated elements are used as direct inputs to the resource model to assist the target element’s grade prediction for every block. The testing methodology for measuring resource model performance is blind; the model’s grade block predictions are compared against held out test data using bootstrap sampling and newly collected drillhole data. We demonstrate that 1) existing techniques for finding correlations between assayed elements do not reflect the complex geology of the asset, 2) non-linear correlations that are difficult to model as simple mathematical functions are representative of geological patterns in a deposit, and 3) non-linear correlated assayed data fed as inputs increase the performance of the resource model as reconciled through blind tests. The model’s performance was further corroborated by a 18% block-by-block accuracy increase (over test samples) in resource model performance by grouping correlated elements as inputs in modeling the target element. Since arsenic and other correlated elements were not assayed for every drillhole, “less than one” data can imbibe a resource model performance boost despite inconsistent sampling.
Deciphering thallium deportment and remobilization in shallow-water massive sulfides at the Kolumbo arc-volcano, Greece: evidence from in situ LA-ICP-MS study and thallium-isotope fractionation

Nikolaos Zegkinoglou, Stephanos P. Kilias, Evangelia Zygouri, Paraskevi Nomikou
National and Kapodistrian University of Athens, Greece

Manuel Keith
Friedrich-Alexander-Universität (FAU) Erlangen-Nurnberg, Germany

Aleš Vaněk
Czech University of Life Sciences Prague, Czech Republic

Martin Mihaljevič, Maria Vaňková
Charles University, Czech Republic

Daniel J. Smith
University of Leicester, United Kingdom

Paraskevi Polymenakou
Hellenic Centre for Marine Research, Greece

Understanding the mechanism(s) of mineralogical deportment and remobilization of Tl, and Tl-isotope fractionation, are key to tracing of Tl enrichment in hydrothermal ore deposits. However, such constraints in modern, arc-related SMS systems, and their ancient analogs VMS deposits, are largely lacking. To address this issue, Tl-rich polymetallic (Au, Ag, As, Sb, Pb, Hg, Mo, Zn and Cu) diffuser chimney samples from the active Kolumbo shallow-water SMS system, Hellenic Volcanic Arc, were geochemically and texturally examined using combined FEG-SEM-EDS imaging, LA-ICP-MS spot analysis and trace element mapping, and bulk Tl isotope measurements. Recrystallized pyrite2 (avg.: 378 ppm Tl) exhibits porosity coexisting with (sub)-micron multiphase inclusions of Tl-bearing sulfide-sulfosalt mineral phases (MUTHSUL) enriched in low-melting point chalcophile elements (LMCE) (Ag-As-Au-Hg-Sb-Tl) suggestive of coupled dissolution-reprecipitation (CDR) replacement of Tl-rich, LMCE-bearing colloform-textured pyrite1 (avg.: 1362 ppm Tl). Similarly, CDR-replacement of Tl-rich (Au-As-Ag-Mo)Pb-Sb sulfosalts (avg.: 405ppm Tl) by PXRD-amorphous orpiment-like As-sulfides, result in the highest reported Tl enrichment in SMS As-sulfides (≤8.2 wt% Tl). Moreover, the MUTHSUL combined with the presence of high-temperature (~265°C) hydrothermal fluids that are highly enriched in LMCEs, are strongly indicative for the generation of a Tl-dominated polymetallic sulfide-sulfosalt melt due to partial melting of early LCME-rich pyrite1. This is supported by significant $\varepsilon^{205}\text{Tl}$ range of >9 units (–2.38 ± 0.7 to +6.96 ± 0.7) in bulk isotope Tl values, which can be explained by Tl-isotope fractionation occurring during fractional crystallization of a sulfide melt in equilibrium with an aqueous fluid, and Tl-rich sulfide precipitation at temperatures lower than 300°C. We propose that polymetallic melts in Tl-rich arc-related SMS systems dominated by hydrothermal fluids, and associated with CDR-replacement processes, can cause expulsion and remobilization of Tl, and sequestration both as MUTHSUL or lattice bound, into Tl-rich sulfides; these processes may have contributed to the uniquely extreme Tl enrichment of the Kolumbo As-sulfides.
Field and drill core hyperspectral analysis is now used widely in the mining industry as a tool to complement traditional mapping and logging techniques. It provides a rapid, non-invasive and cost-effective analytical method to identify footprints of hydrothermal mineral systems, vector towards potential ore bodies and differentiate domains in ore deposits. However, the use of hyperspectral data, particularly thermal infrared spectral data, to characterize skarn mineralogy has been mostly restricted to a few case studies.

The Dolphin deposit on King Island, Tasmania, Australia, is a large tungsten skarn with reserves of 4.43 Mt @ 0.92% WO₃ (King Island Scheelite Ltd 2020). The ore mainly consists of scheelite-bearing garnet-pyroxene skarn, replacing Neoproterozoic layered carbonate-volcaniclastic units adjacent to a Carboniferous granitoid. There are significant spatial variations of garnet, pyroxene and amphibole species, making Dolphin an ideal candidate for evaluating hyperspectral sensing for rapid and reliable mineral characterization of skarn deposits.

Hyperspectral visible-near, shortwave, and thermal infrared data were collected from drill core and field samples of the Dolphin deposit, using the hyperspectral drill core scanning system “HyLogger-3”. Compositional variations of garnets in Dolphin were successfully determined using a combination of three major TIR-active absorption peaks due to inner SiO₄ tetrahedra stretching modes in the 10 to 12 μm wavelength region. From proximal to distal towards the high-grade ore zone, one of the absorption peaks of garnet varies from ~11,470nm to 11,396 nm. Our results indicate that combined hyperspectral and mineral chemistry analytical methods can effectively characterize skarn mineralogy and potentially aid W skarn exploration globally.