

Whole-rock geochemistry for intrusion-hosted magmatic Ni-Cu-Co exploration: identifying prospective host rocks

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Introduction

Nickel, copper and cobalt are hot targets for today's explorers. Demand is projected to rise and keep rising with the expected upsurge in demand for the electric vehicle market. Magmatic sulfide deposits host all of these elements, plus in many cases significant quantities of platinum group elements (PGEs), so a good discovery is a holy grail for the mining industry. Even relatively small deposits by global standards, such as the Savannah deposit in the Kimberley region of Western Australia, contain billions of dollars' worth of metals (about AU\$3.5 billion for Savannah at February 2022 spot prices). The supergiant Oktyabrynsky orebody in the Norilsk-Talnakh ore camp in arctic Siberia (Russia), contains what is probably the most valuable single ore deposit of any type on the planet, with premining resources estimated at 13 million tonnes Ni, 24 million tonnes Cu and 4700 tonnes PGEs (Barnes *et al.* 2020). At current prices, the pre-mining metal content of this extraordinary deposit (discovered in the 1960s) is worth well in excess of half a *trillion* Australian dollars. Therefore, important questions for the reader include what are magmatic sulfide deposits and how can we use geochemistry as a tool in exploring for them?

Magmatic sulfide deposits are analogous to nature's smelters. By the same process that has been used since prehistoric times to extract metals from ores, magmatic sulfide ores form by the interaction between immiscible sulfide-oxide liquids (mattes) with silicate magmas (slags). Scavenging of chalcophile elements – Ni, Cu, Co, Au and PGEs – and the accumulation of the matte component has produced the deposits that currently account for ~56% of the world's Ni production and over 96% of Pt and Pd production (Mudd and Jowitt 2014).

Australia (specifically Western Australia) is well-endowed with this deposit type. The Archean East Yilgarn nickel province is the third largest magmatic nickel province in the world after Sudbury (Canada) and Norilsk-Talnakh, containing well over ten million tonnes of nickel metal on a premining basis (Hronsky and Schodde 2006; Barnes and Fiorentini 2012). These deposits are hosted in komatiites, the ultra-hot lava flows that are the signature volcanic rock of the first half of Earth history. However, the komatiite belts of Western Australia have been very extensively explored, and while new deposits are discovered from time to time (such as Mincor's 2015 Cassini discovery near Widgiemooltha, 1.2 million tonnes at 4% Ni), it is relatively unlikely that giant undiscovered deposits still exist at accessible depths. Consequently, a large effort has been focussed internationally to discover the second and globally most important type of Ni-Cu-Co sulfide deposits: those hosted in deep-seated mafic-ultramafic intrusions formed by basaltic magmas. Australian explorers have had some major successes in finding these deposits in recent years, with the discovery of Nova-Bollinger (2012), Gonnevillie (Julimar) (2020) and Savannah North (2014). This category includes most of the world's giant deposits, including those at Norilsk-Talnakh and is the topic of this article.

Intrusion-hosted Ni-Cu-Co deposits are really tough targets. Explorers speak of distal footprints: the broad signal of ore forming processes that extends beyond the dimensions of the deposits themselves and effectively increases the size of the target. In many other deposit types, such as porphyry copper or orogenic gold deposits, there is a broad halo of hydrothermal alteration and anomalous geochemical signatures that occupies many times the volume of the actual orebodies. Such haloes rarely if ever exist in magmatic sulfide systems. The distal geochemical and mineralogical signals of magmatic ores can, in most cases, only be found within the magma transport network within which they form. These networks take the form of interconnected sills, dykes, conduits and magma chambers having a wide range of sizes, shapes and internal structures (Barnes *et al.* 2016a).

As research scientists, we aim to apply our understanding of ore forming processes to exploration in two main ways: improved prediction of where to look for prospective terranes, and improved detection to find the needle in the haystack at the prospect or deposit scale. These approaches are commonly combined nowadays into a "mineral system" approach, where deposits are seen holistically in a multi-scale framework from lithospheric-scale magma transport to the local mechanisms of deposit formation (Barnes *et al.* 2016a). It's now well established that major deposits tend to be located near craton margins – that is, near the edges of the ancient building blocks of the continental crust (Begg *et al.* 2010). However, this targeting only narrows down the prospective terranes to a scale of tens or even hundreds of km, so moving into the detection stage becomes rapidly harder and more expensive.

At CSIRO (Commonwealth Scientific and Industrial Research Organisation) Mineral Resources group, we have been focussed for the last few years on identifying prospective host rocks through a better understanding of the physics of the ore forming processes. Igneous intrusions are plentiful in prospective belts such as the Albany-Fraser orogen



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Notes from the Editor

Welcome to the second **EXPLORE** issue of 2022. This issue features an article describing the use of whole-rock geochemistry for intrusion-hosted magmatic Ni-Cu-Co exploration and was written by Steve Barnes. **EXPLORE** thanks all those who contributed to the writing and/or editing of this issue, listed in alphabetical order: Steve Amor, Dennis Arne, Al Arsenault, Steve Barnes, John Carranza, Michel Houllé, David Leng, Jessey Rice, Dave Smith, Monica Sorondo, and Brian Townley.

Beth McClenaghan
Editor

Steve Cook,
Business Manager



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in Western Australia, or the Siberian Traps flood basalt sequence in arctic Russia, but the proportion of intrusions that contain orebodies can be vanishingly tiny. In the Siberian example, the ore-bearing intrusions account for less than one part per million of the total volume of basaltic magma in the province (Barnes *et al.* 2020). In the Albany-Fraser Orogen this proportion is unknown, but one volume percent ore-bearing would be a conservative order-of-magnitude guess. A typical exploration program will encounter large volumes of potentially “fertile” rocks, the challenge being to then reduce the search space to the most promising targets. The challenge, particularly in poorly outcropping or covered terranes, lies in extracting the maximum amount of useful information from drill intersections of barren rocks. Can a small number of sulfide-free samples from the distal portions of an ore-forming system (Fig. 1) be used to identify prospectivity or vector towards ore?

It is commonly accepted that ore formation happens within magmatic plumbing systems that are active over prolonged

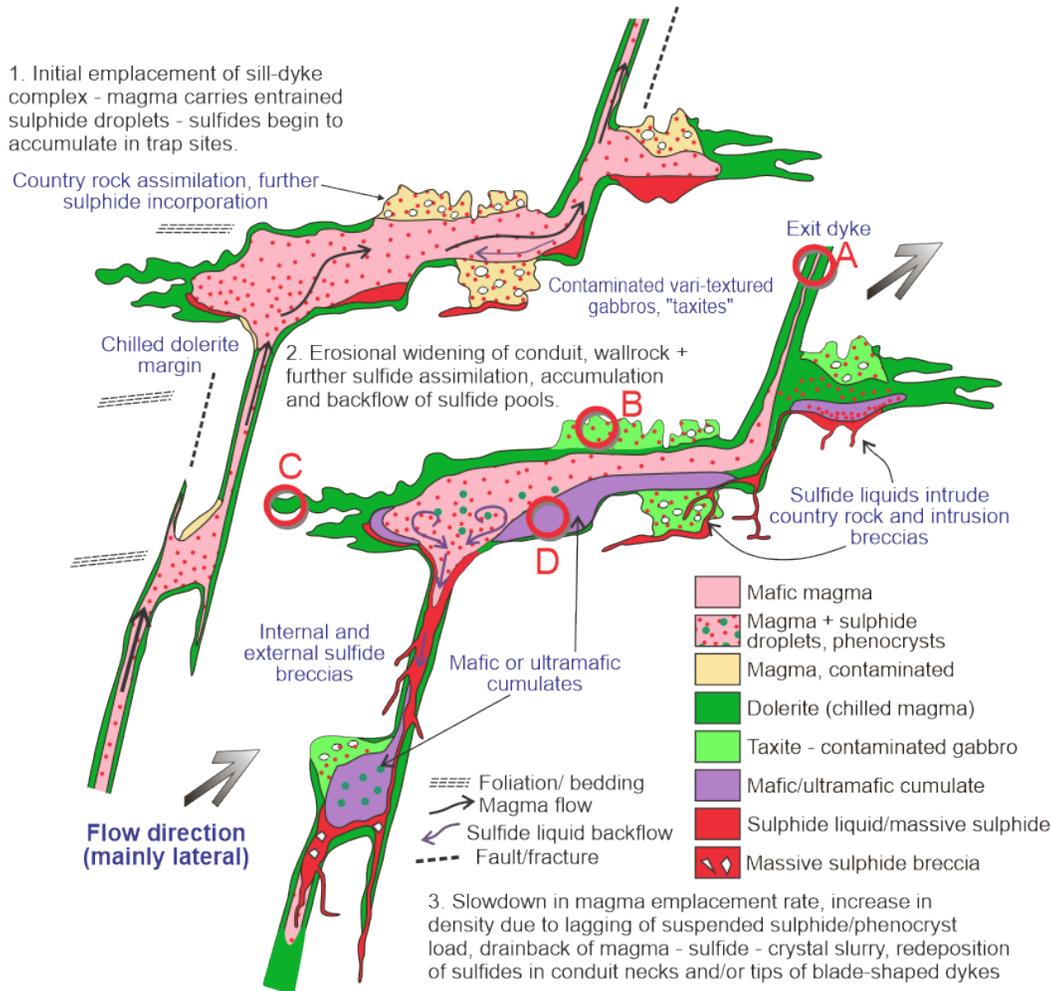


Figure 1. Schematic diagram showing two stages in the development of an intrusion-hosted Ni-Cu-Co sulfide system, modified from Barnes *et al.* (2016a). Ore deposition takes place within part of a larger sill-dyke network with multi-stage assimilation, transport and deposition (Stage 1), re-entrainment and backflow of sulfide liquid droplets and pools (Stage 2) and final deposition during drain-back at the waning stages of magmatism (Stage 3). Geochemical anomalies indicative of ore formation can be present in several components of the system. A) “exit dyke” sampling silicate melt, potentially depleted or enriched in chalcophile elements; B) contaminated marginal taxites with anomalous mineralogy and/or whole rock chemistry; C) distal margins of offshoot dykes and sills preserving early-stage emplacement and transported sulfide droplets; D) cumulate rocks in deposition sites extending beyond sulfide ores – anomalous mineral chemistry and zoning.

periods of time, experiencing multiple pulses of magma injection (Lightfoot and Evans-Lamswood 2015; Barnes *et al.* 2016a; Leshner 2019). The cartoon in Figure 1 illustrates this type of environment. Basaltic magma derived from the mantle flows (mostly sideways) through interconnected fracture networks in the crust (Magee *et al.* 2016). The critical sulfide component is derived by incorporating fragments of sulfide-bearing wall rock into the magma and melting them (Fig. 1, stage 1). The resulting sulfide liquid matte is very dense, and so has a strong tendency to sink out of the magma (Fig. 1, stage 1), but is also easily recycled and carried along as dispersed droplets (Leshner 2019; Yao *et al.* 2020). Based on detailed studies of the sulfide-silicate textures in the deposits themselves, and on analogies with modern volcanic systems, Barnes *et al.* (2016a) proposed that major deposits form in the waning stages of these plumbing systems where slurries of magma, sulfide droplets, crystals and rock fragments flow backwards and downwards into trap sites, often invading and intruding their own host rocks (Fig. 1) (Taranovic *et al.* 2022). How can these conceptual models be used to inform targeting decisions? How can maximum value be added to exploration data, particularly whole-rock chemical analyses and geochemical databases?

Modern exploration programs collect colossal volumes of geochemical data. Most commercial laboratories now offer ICP-MS or ICP-OES analyses of 40 or more elements per sample, and tens of thousands of samples can be (and often are) analysed during an extensive exploration program. The secret to obtaining the best value from these large datasets lies in using the data to answer specific questions arising from mineral system models (Fig. 1). Here are three main ones:

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1. Is there evidence for the presence and/or deposition of sulfide liquid droplets?
2. Is there evidence that the magmas have been interacting with their country rocks along the flow pathway?
3. Are the samples at or close to a deposition site, where suspended silicate crystals are being deposited from the magma to form cumulate rocks?

Clearly if the answer to the first question is positive, this is by far the best geochemical indicator of magmatic ore formation. But there are many examples of near-misses where lack of evidence of sulfide in rocks from an unmineralized part of an ore-bearing intrusive system could generate a false negative. Furthermore, signals of country rock interaction, in the form of geochemical indicators of wall-rock contamination of the magma, can be flushed out by uncontaminated fresh magma within the flow pathways. On the other hand, there are very few, if any, examples of ore forming systems where there is not a positive answer to question 3 so we focus on this aspect now.

Identifying cumulate rocks from geochemistry

Deposition sites are marked by the presence of cumulate rocks: the solid products of fractional crystallisation (Fig. 2A). Cumulates are rocks made up primarily of the crystals that were separated from the magma they crystallised from, plus a smaller component of that magma trapped between the crystals. Where they are dominantly ultramafic, i.e. made up of high proportions of ferromagnesian igneous minerals such as olivine and pyroxene, they are easy to recognise. Nevertheless, where they contain cumulus plagioclase in addition to olivine and pyroxene they can be much harder to recognise, as the cumulus mineral assemblage is not greatly different from the mineralogy produced by isochemical solidification of the magma. Ore-bearing intrusions typically contain a high proportion of cumulate rocks, such that understanding their origin and chemistry is crucial to unravelling geochemical data sets in magmatic sulfide exploration. Figure 2 shows the petrological basis for this understanding in the framework of standard phase diagrams.

The main messages from the phase diagrams are these.

1. Ultramafic rocks are not necessarily derived from ultramafic magmas. In fact, most "normal" mantle derived basalts can generate ultramafic cumulates, provided that they haven't evolved too far from their original compositions.
2. A very minor change in the chemistry of the magma can cause a significant change in the cumulate rock it pro-

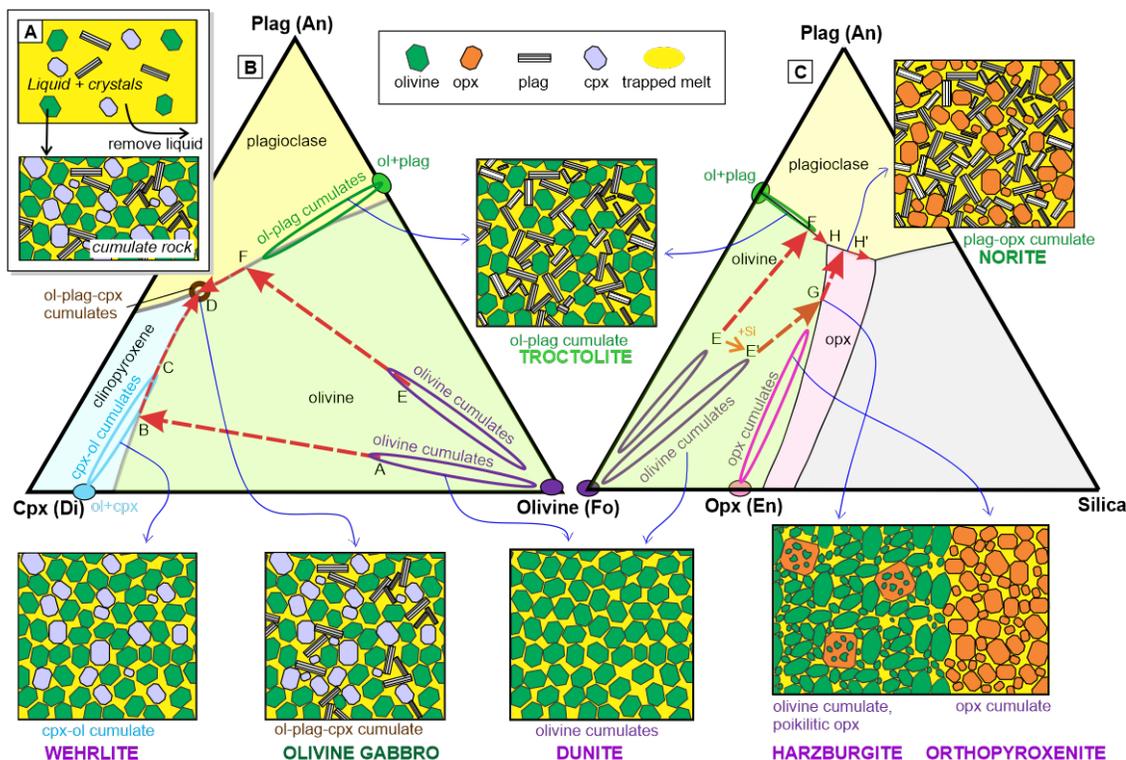


Figure 2. Phase diagrams from the "basalt tetrahedron" (Irvine 1970) showing crystallisation sequences of basaltic liquids in the simplified "basalt tetrahedron" system olivine (ol), forsterite (Fo) – clinopyroxene (cpx), diopside (Di) – plagioclase (plag), anorthite (An) – silica (Si), which includes orthopyroxene – enstatite (En). Coloured fields indicate the first phase to crystallise, red dashed line indicate the down-temperature path of evolution of the liquid during perfect fractional crystallisation (crystals removed from the liquid as they form – inset A). Cumulate fields indicate the compositions of the rocks formed as mixtures of cumulus crystals and their parent liquids.

For example in the Fo-Di-An projection (B), liquid A crystallises ol, evolves to point B, crystallises ol+cpx along path B-C, C-D. At D, plag begins to crystallise giving rise to an olivine gabbro, olivine+cpx+plag. Liquid E crystallises ol, evolves to point F, follows a path E-F-D giving ol, ol + plag (troctolite), olivine gabbro. If liquid A crystallises to a solid of its own composition, it will produce a non-cumulate rock made mostly of ol, cpx and plag. In the Fo-An-Silica projection (C), liquid E follows the same sequence as in the F-Di-An projection, giving ol, ol + plag (troctolite), olivine gabbro. However, crystallisation of a slightly more silica enriched composition E' is complicated by a "peritectic" phase boundary where olivine reacts with the liquid to form orthopyroxene (Opx-En, enstatite)– path E'-G-H-H' giving rise to distinctive poikilitic harzburgite, and eventually norite.

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duces, e.g. from a peridotite (ultramafic - olivine+pyroxene) to a troctolite or a olivine gabbro (mafic) at the first appearance of plagioclase (points F, D, H in Figure 2); these phase appearances are commonly present as sharply-bounded layers in ore-hosting intrusions. They do not require new magma pulses.

3. A small change in the “starting composition” can cause a big change in crystallisation sequence: e.g. changing the starting composition from E to E' in Figure 2C, by adding a small amount of silica, causes the crystallisation path to change from dunite-troctolite-norite along the path E-F-H-H' to dunite-harzburgite-orthopyroxenite-norite along path E'-G-H'. The harzburgites formed in this way have a characteristic texture called “poikilitic” where large grains of orthopyroxene enclose many smaller, partially dissolved crystal of olivine. This is probably the most widespread rock type associated with intrusion-hosted Ni-Cu-Co deposits.
4. The further down the crystallisation path, the more the solid cumulate product chemically resembles the magma, the harder the cumulate is to recognise.

Armed with this basic understanding, whole rock geochemistry is easier to interpret. All of these rock types can be readily distinguished in geochemical data sets. For example, Figure 3 shows an easy way to distinguish a cumulate gabbro (indicating a deposition site – position D in Figure 1 from a mineralogically similar rock that simply represents the

Table 1. Data sources.

Locality/Belt	Source of data
Albany-Fraser Orogen regional and Nova-Bollinger deposit	(Smithies <i>et al.</i> 2013), (Taranovic <i>et al.</i> 2022), (Bathgate 2019)
Halls Creek Orogen and Savannah/Savannah North deposits	(Mole <i>et al.</i> 2018), (Le Vaillant <i>et al.</i> 2020), Geological Survey of WA WACHEM database, https://catalogue.data.wa.gov.au/dataset/?tags=WACHEM
Kimberly Craton Hart Dolerite	Geological Survey of WA WACHEM database, https://catalogue.data.wa.gov.au/dataset/?tags=WACHEM
Mozambique Mobile Belt, Ntaka Hill deposit	(Mole <i>et al.</i> 2017), (Barnes <i>et al.</i> 2016b)

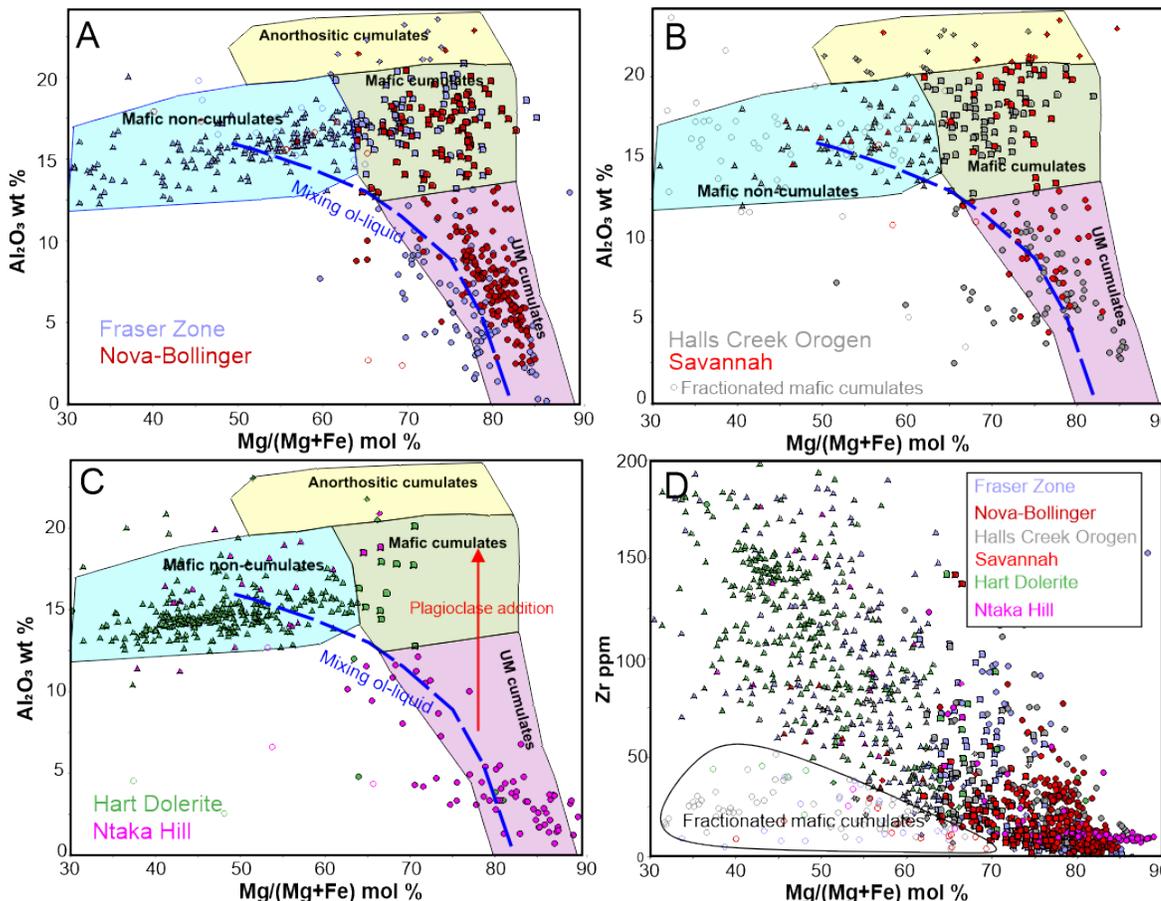


Figure 3. Discriminant plot for ultramafic (UM) and mafic cumulates and non-cumulate mafic rocks. Whole rock data, Al_2O_3 wt % versus Mg number ($\text{Mg}\#$, molar percent $\text{MgO}/[\text{MgO}+\text{FeO}]$). Cumulate rocks have higher $\text{Mg}\#$ due to Fe-Mg minerals always having higher $\text{Mg}\#$ than the magmas they crystallise from. Individual plots show data for (A) the Fraser Zone of the Albany-Fraser orogen, comparing regional mafic rocks with the host intrusion to the Nova-Bollinger deposit; (B) Halls Creek orogen data compare regional mafic-ultramafic intrusions with the Savannah deposit host intrusion; and (C) the Hart Dolerite is an

extensive unmineralised suite of dolerite sills in the Kimberley Craton, showing an almost complete absence of ultramafic cumulates and the Ntaka Hill deposit, hosted by an almost entirely ultramafic host body containing an abundance of orthopyroxene cumulates.

(D) Plot of whole rock Zr vs Mg number, showing field for mafic cumulates derived from strongly fractionated Fe-rich parent magmas. See Table 1 for data sources.



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magma crystallising to a solid of the same composition – such as might be found in a chilled margin, for example (position C, Figure 1). Spatially mapping out ultramafic and gabbroic cumulates from non-cumulate chilled liquid rocks using spatially constrained geochemical datasets provides a powerful tool for unravelling the internal structure of a potentially fertile magmatic system.

Not all ore-hosting intrusions contain ultramafic cumulates, where the cumulus phases are combinations of

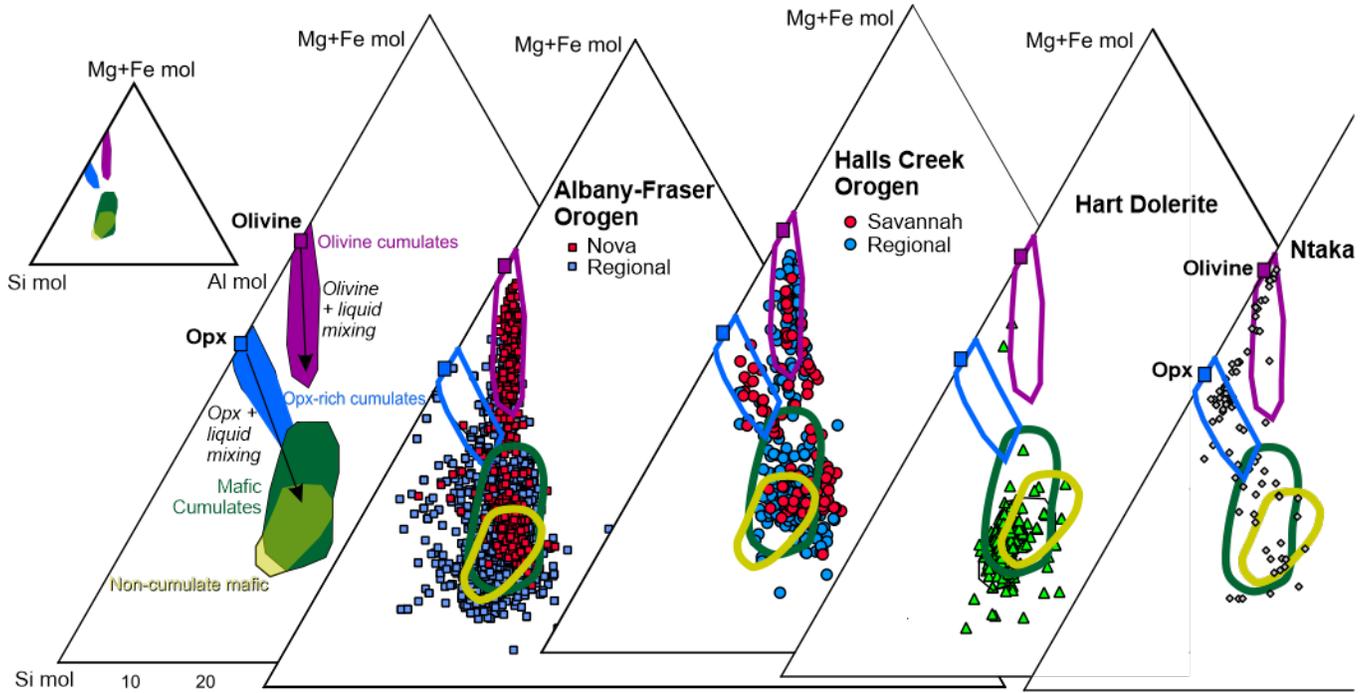


Figure 4. Triangular plot – molar ratio of MgO + FeO, SiO₂ and Al₂O₃ (see Table 2 for the calculation method) for discrimination of olivine and orthopyroxene (opx) dominated cumulates from cumulate and non-cumulate gabbros. Same data sets as Figure 3.



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Table 2. Factors for calculating molar components.

Mg mol	MgO/40.3
Fe mol	[Total Fe as FeO*]/71.9
Si mol	SiO ₂ /60.1
Al mol	Al ₂ O ₃ /51
Mg#	Mg mol/[Mg mol + Fe mol]

*in cumulate rocks we neglect the component of Fe present as Fe₂O₃. This introduces a small positive error, up to about relative 5%, in orthocumulates.

olivine, pyroxene and (usually) minor chromite, but there are very few that don't. As can be seen in Figures 3, the ore-bearing intrusions in a number of prospective belts are strongly dominated by cumulate rocks compared with other mafic rocks in the same belt, a particularly clear example being the Nova intrusions in the Albany Fraser orogen. The Hart Dolerite represents a very high-volume Large Igneous Province almost completely devoid of cumulate rocks, and has so far proved entirely barren for this deposit type. This would be typical of the signatures of unmineralized suites of mafic rocks.

Recognising ultramafic cumulate rocks is generally fairly straightforward: they are high in Mg, Cr and Ni and low in components such as Al and Ti that are not concentrated in these minerals. However, ultramafic rocks are very susceptible to alteration, which can modify their chemistry, and weathering, which is discussed in the next section. Orthopyroxene is a particularly useful indicator, in that most mantle-derived

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magmas don't crystallise much of it. The presence of orthopyroxene cumulates is a good indication that magmas have been contaminated with silica-rich country rocks (causing the shift from composition E to E' in Figure 2C), which is another positive indicator for fertility.

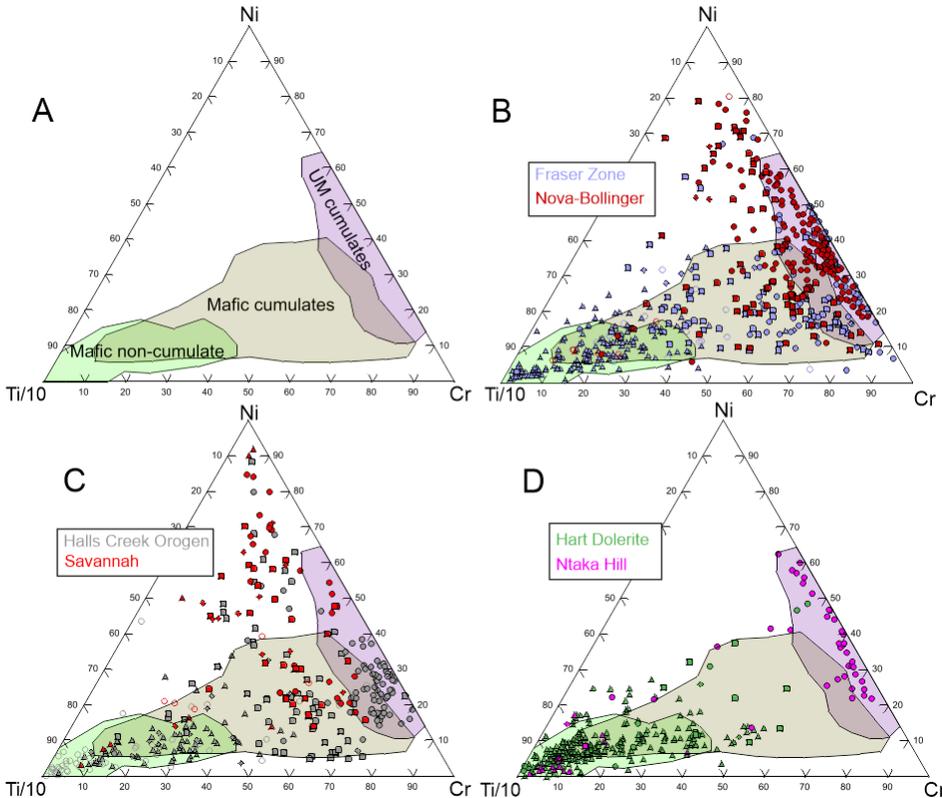


Figure 5. Ni-Cr-Ti triangular plot, same format and data sets as Figure 4.

Weathered and/or altered rocks

Weathering and alteration commonly cause chemical changes in rocks, with the more soluble elements such as Na, K, Ca, Mg, Cu, Zn and sometimes Si being most affected. In the case of deeply weathered terranes common in Australia, exploration programs commonly sample leached rocks where some or all of these elements have been largely stripped. The solution to this problem is to use relative proportions of the relatively immobile elements, on the assumption that the ratios of these elements to one another do not change during alteration or mild weathering. We investigated the best element combinations using a dataset from the Agnew area in Western Australia where we had excellent sampling of fresh rocks and their overlying weathered equivalents (Barnes *et al.* 2014), and found that the following elements can be reliably used in this way: the rare earths (REE), Ti, Al, Sc, Zr, Hf, Cr and, except in cases of advanced lateritic weathering, Ni. Consequently, plots using combinations of these elements such as Ni/Ti, Ni/Cr and Al/Ti, or triangular plots using combinations of these elements, as shown in Figure 5, are reliable discriminants of rock type in moderately weathered or altered rocks. This is particularly useful in identifying cumulate rocks from bottom-hole samples from percussion drilling programs. Furthermore, Ni, Cr and Ti are reliably determined by portable XRF on percussion chips or air core, making this combination particularly useful in reconnaissance greenfields exploration (Le Vaillant *et al.* 2014, 2016).

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Figure 4 shows a geochemical technique that allows the recognition of olivine and orthopyroxene cumulates from whole-rock geochemistry, to be used in conjunction with Figure 3. It is important to note that this method requires reliable SiO₂ analyses, which are not provided in some element suites such as the standard ICP-OES package offered by many commercial laboratories. Silica is such an important component that it's generally worth spending more money to analyze it using the more comprehensive ICP-MS method, even if that is at the expense of dropping off some of the lower-abundance trace elements like Se, Te and Bi that are typically below the limit of detection in cumulate rocks. The mineralised Ntaka Hill intrusion in Tanzania (Barnes *et al.* 2019) shows up clearly as an intrusion with abundant orthopyroxene cumulates (Fig. 4).

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Concluding remarks

Successful exploration involves weighing multiple lines of evidence. In the case of magmatic sulfide deposits, the evidence might include the presence of cumulates, textural or geochemical evidence for existence of sulfide liquids, geochemical indicators of wall rock contamination using strongly incompatible lithophile elements such as light rare earth elements and Th (Leshner *et al.* 2001; Le Vaillant *et al.* 2016), pyroxene zoning (Schoneveld *et al.* 2020), anomalous chemistry in other indicator minerals like olivine and chromite (Locmelis *et al.* 2018; Barnes *et al.* 2022), and of course the presence of encouraging geophysical anomalies (Peters 2006). Any of these signals can generate false positives and negatives. The presence of high proportions of cumulate rocks in small intrusions (less than a few hundred metres in thickness) is one of the best “distal footprint” indicators, particularly if they contain traces of magmatic sulfide.

It is not possible to go into more detail about the many potential applications of whole-rock geochemical datasets in this short article, but we have prepared a set of short course notes, iGas diagram templates and Python libraries that can be examined fully on our CSIRO Magmatic Sulfides Systems website (<https://research.csiro.au/magnico/workshops-and-resources/>) for free download. We encourage readers to investigate this toolkit, and to contact us to request help with using it.

There are no silver bullets. It may be that AI-based automated decision making may take over in future in the process of weighing the evidence, but it is likely that application of sound principles of igneous petrology and geochemistry will prevail for a few decades. Either way, the best strategy is to make the most intelligent use of data to answer critical questions, rather than drowning in vast volumes of indigestible numbers. As we noted earlier, these are difficult targets to find. The upside of that is that there are almost certainly major discoveries yet to be made.

Acknowledgments

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continued on page 13

Whole-rock geochemistry for intrusion-hosted magmatic... *continued from page 12*

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Call for AAG Medal Nominations

Significant contributions to applied geochemistry or service to AAG are recognised by award of either the AAG Gold or Past Presidents' (Silver) medals respectively. The history of how the medals came about and the formulation of guidelines for their award are discussed in the April 1992 issue of **EXPLORE**, issue 75, which can be found on the AAG website.

Guidelines for nominating individuals for either medal are posted in 'The Association' section of the AAG website (www.appliedgeochemists.org) under the 'Awards' area. Past discussions of the guidelines indicated that the process for nominating individuals for either medal was a little cumbersome, to the extent that some nominations were not being made, and others took an unnecessarily long time to resolve. With this in mind, the 2012-2013 Awards & Medals Committee (Chair: Paul Morris. Committee members Eion Cameron, Pertti Sarala, and Chris Benn) revisited the guidelines to make the nomination process a little friendlier, with a more concise timeframe for resolution. The revised guidelines for nominations are presented below.

3.0 NOMINATIONS

3.1 To be eligible for consideration for either award, nominations must be received by the Chairman of the Awards and Medals Committee on or before December 1st of any year.

3.2 For acceptance by the Awards and Medals Committee, nominations must be signed by a minimum of four (4) Fellows (voting members) of the Association in good standing. Nominations should include:

- (a) A one page recommendation from each of the four nominators;
- (b) A resume or curriculum vitae of the nominee;
- (c) An itemized list of the outstanding scientific achievements (Gold Medal) or the dedicated service to the Association (Silver Medal) of the nominee (maximum two pages).

Since members of the Awards Committee may not have personal knowledge of the nominee, the completeness and quality of the nomination will be critical in terms of evaluation and selection.

Nominations for either medal can be made any time to arne.dennis@gmail.com and will be considered in the year following nomination provided they are received prior to December 1.

Dennis Arne

Past President

Chair, Awards and Medals Committee



Recently Published in Elements

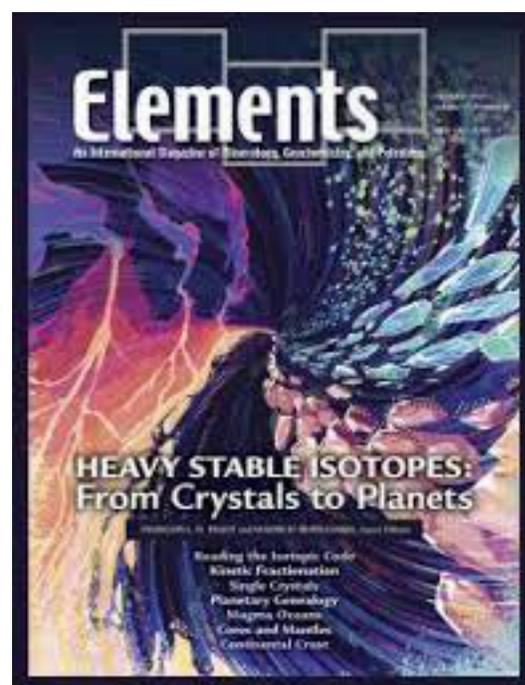
*December 2021, volume 17, no. 6,
Heavy Stable Isotopes: From Crystals to Planets*

The articles in this issue explore the enormous range of temporal and physical scales over which heavy stable isotopes have provided paradigm-shifting insights into the evolution of our planet and solar system. This issue also highlights new frontiers where novel stable isotope systematics appear particularly promising for unraveling long-standing questions.

There are two AAG news items in this issue. The first is a citation for Robert G. Garrett, who was awarded Honorary Fellowship in AAG. The second is an abstract of an article that appeared in issue 190 (February 2021) of the **EXPLORE** newsletter, namely "Geochemical Variables as Causality Co-Factors in Diseases of Unknown Aetiology (DUA) in Africa" by T.C. Davies.

Reminder: AAG members can access past issues of Elements at <http://elementsmagazine.org/member-login/> using their e-mail address and member ID.

John Carranza



Geochemistry: Exploration, Environment, Analysis, Volume 22, Number 2

Research Article

Identification of stream sediment geochemical anomalies in lithologically complex regions: case study of Cu mineralization in Hunan province, SE China

Yaoyao Sun, Libo Hao, Xinyun Zhao, Jilong Lu, Yanxiang Shi, Chengyou Ma, Qingquan Li and Qiaoqiao Wei

doi:10.1144/geochem2021-096

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2021-096/612481/Identification-of-stream-sediment-geochemical?redirectedFrom=fulltext>

Thematic collection: Applications of innovations in geochemical data analysis

Quantitative prediction of prospectivity for Pb-Zn deposits in Guangxi (China) by back-propagation neural network and fuzzy weights-of-evidence modelling

Shuyun Xie, Ning Huang, Jun Deng, Songle Wu, Mingguo Zhan, Emmanuel John M. Carranza, Yuepeng Zhang and Fanxing Meng

doi:10.1144/geochem2021-085

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2021-085/611082/Quantitative-prediction-of-prospectivity-for-Pb-Zn?redirectedFrom=fulltext>

Google Earth-aided visualization and interpretation of geochemical survey data

Renguang Zuo and Bojun Yin

doi:10.1144/geochem2021-079

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2021-079/612880/Google-Earth-aided-visualization-and?redirectedFrom=fulltext>

Geochemical characteristics and indication of graphite deposits in Xinrong Region, Shanxi, China

Yuqi Liang, Qinglin Xia, Yue Zhang and Yong Zhao

doi:10.1144/geochem2021-086

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2021-086/612889/Geochemical-characteristics-and-indication-of?redirectedFrom=fulltext>

Evaluation of magnetite as an indicator mineral for porphyry Cu exploration: a case study using bedrock and stream sediments at the Casino porphyry Cu-Au-Mo deposit, Yukon, Canada

Martin W. McCurdy, Jan M. Peter, M. Beth McClenaghan, Michael G. Gadd, Dan Layton-Matthews, Matthew I. Leybourne, Robert G. Garrett, Duane C. Petts, Simon E. Jackson and Scott Casselman

doi:10.1144/geochem2021-072 **OPEN ACCESS ARTICLE**

<https://pubs.geoscienceworld.org/geea/article/22/2/geochem2021-072/612584/Evaluation-of-magnetite-as-an-indicator-mineral>

Thematic collection: Hydrochemistry related to exploration and environmental issues

Hydrogeochemistry of porphyry-related solutes in ground and surface waters; an example from the Casino Cu-Au-Mo deposit, Yukon, Canada

J. A. Kidder, M. B. McClenaghan, M. I. Leybourne, M. W. McCurdy, P. Pelchat, D. Layton-Matthews and A. Voinot

doi:10.1144/geochem2021-058 **OPEN ACCESS ARTICLE**

<https://pubs.geoscienceworld.org/geea/article/22/2/geochem2021-058/610742/Hydrogeochemistry-of-porphyry-related-solutes-in>



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Geochemistry: Exploration, Environment, Analysis... *continued from page 15*

Removal of Mn²⁺ in geothermal water by manganese sand: process and mechanisms

Wenchao Feng, Jun Wu and Jian Lu

doi:10.1144/geochem2021-071

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2021-071/610914/Removal-of-Mn2-in-geothermal-water-by-manganese?redirectedFrom=fulltext>

Controls on groundwater selenium, arsenic and base metals in groundwater around a selenium-bearing volcanogenic massive sulfide deposit: constraints from stable isotopes, trace elements and redox controls

Matthew I. Leybourne, Daniel Layton-Matthews, Jan M. Peter and James A. Kidder

doi:10.1144/geochem2021-063

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2021-063/610913/Controls-on-groundwater-selenium-arsenic-and-base?redirectedFrom=fulltext>

Comparison of groundwater composition from the Monturaqui and Punta Negra Basins, northern Chile: implications for porphyry copper exploration

C. W. F. Rissmann, M. I. Leybourne, C. Benn, J. A. Kidder and L. K. Pearson

doi:10.1144/geochem2021-056

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2021-056/611780/Comparison-of-groundwater-composition-from-the?redirectedFrom=fulltext>

Obituary

John Somerville Tooms (1927-2021)

doi:10.1144/geochem2022-004

<https://pubs.geoscienceworld.org/geea/article-abstract/22/2/geochem2022-004/611983/John-Somerville-Tooms-1927-2021?redirectedFrom=fulltext>

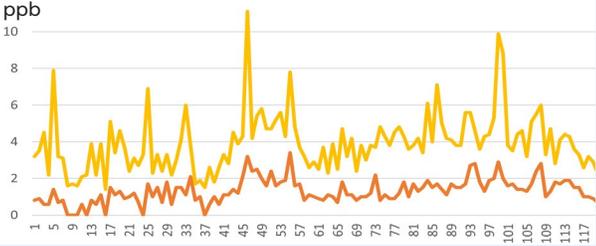


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Third Circular

IAGS2022 is held in memory of Professor Dr. Peter Winterburn (1962 – 2019)

The **Local Organizing Committee (LOC)**, the **Association of Applied Geochemists (AAG)** and the **Sociedad Geológica de Chile (SGCh)** are proud to announce the **29th International Applied Geochemistry Symposium, IAGS2022 Viña del Mar, Chile**.

The 29th IAGS was originally scheduled to take place in Viña del Mar in November 2020. However, in view of the worldwide coronavirus pandemic, the LOC, in accordance with the AAG and SGCh decided to postpone the event until October 2022, aiming for a face-to-face meeting, and potentially holding a hybrid mode with live streaming for online participants.

IAGS2022 is organized by the **Local Organizing Committee (LOC)** and the **Technical Committee (TC)**.

The **LOC** is constituted by Dr. Brian Townley, President (Universidad de Chile), Dr. Joseline Tapia, Vice-President (Universidad Católica del Norte), and LOC members MSc. Germán Ojeda, Treasurer (Antofagasta Minerals), Dr. Pamela Castillo (Universidad de Concepción), Dr. Paula Ramírez (Flow Hydro Consulting), MSc. Fernando López (BHP Minerals), MSc. Sofía López (ICASS, France), MSc. Carolina Soto (WSP), Dr.(c) McLean Trott (GoldSpot Discoveries Corp., Canada), MSc. Catalina Siebert (Geológica SpA), Dr. María Isabel Varas-Reus (Universität Tübingen, Germany) and Dr. Carmina Jorquera, Chair of the Technical Committee (Teck Resources Ltd.).

The **Technical Committee (TC)** is constituted by renowned researchers and individuals of the industry and academia.

Dates and Venue

IAGS2022 will be inaugurated on Sunday October 23rd, 2022. The Scientific Program will be carried out between Monday October 24th and Friday October 28th, 2022.



Welcome New AAG Members

Regular Members

Members are non-voting members of the Association and are actively engaged in the field of applied geochemistry at the time of their application and for at least two years prior to the date of joining.

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Fellows are voting members of the Association and are actively engaged in the field of applied geochemistry. They are Regular AAG Members that are nominated to be a Fellow by a Fellow of the Association by completing the Nominating Sponsor's Form. Consider becoming a Fellow of the AAG. Download the form here: <https://www.appliedgeochemists.org/>

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Student Members are students that are enrolled in an approved course of instruction or training in a field of pure or applied science at a recognized institution. Student members pay minimal membership fees.

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Lebowakgomo, Limpopo
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Gauteng, Free State
SOUTH AFRICA 0184
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Lawley, C.J.M., McCafferty, A.E., Graham, G.E., Gadd, M.G., Huston, D.L., Kelley, K.D., Paradis, S., Peter, J.M., and Czarnota, K. 2021. Datasets to support prospectivity modelling for sediment-hosted Zn-Pb mineral systems. Geological Survey of Canada, Open File 8836. <https://lnkd.in/eM8sShmy>



CALENDAR OF EVENTS

International, national, and regional meetings of interest to colleagues working in exploration, environmental and other areas of applied geochemistry. These events also appear on the AAG web page at: www.appliedgeochemists.org.

The status of the meetings was confirmed on May 12th 2022, but further changes are likely, and users of the listing are strongly advised to carry out their own research as to the validity of an announcement.

Please let us know of your events by sending details to:
 Steve Amor, Email: steve.amor2007@gmail.com
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Tom Meuzelaar, AAG Webmaster, tom@lifecyclegeo.com

2022

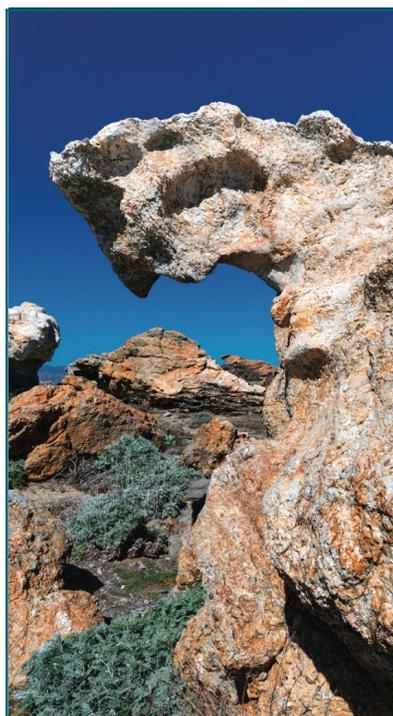
Virtual Meetings

- 28-29 JUNE Prospectors and Developers Association of Canada Annual Convention (online section). Website: www.pdac.ca/convention
- 24-29 JULY 15th International Conference on Mercury as a Global Pollutant. Website: tinyurl.com/2ch7e6fa

In-Person or Hybrid Meetings

- 20-22 JUNE Geoconvention 2022. Calgary AB Canada. Website: geoconvention.com
- 26-29 JUNE International Congress on 3D Materials Science. Washington DC USA. Website: exhpo.com/int/3dms
- 3-6 JULY XII South American Symposium on Isotope Geology. Santiago Chile. Website: ssagi.science
- 10-15 JULY Goldschmidt 2022. Honolulu HI USA. Website: tinyurl.com/3p95at6w
- 11-14 JULY 9th Annual International Conference on Geology & Earth Science. Athens Greece. Website: www.atiner.gr/geology
- 13-16 JULY Euroscience Open Forum 2022. Leiden Netherlands. Website: www.esof.eu
- 13-15 JULY SIAM Conference on Mathematics of Planet Earth. Pittsburgh PA USA. Website: www.siam.org/conferences/cm/conference/mpe22
- 14-16 JULY 7th International Conference on Water Pollution and Treatment. Frankfurt Germany. Website: www.icwpt.net
- 16-18 JULY 5th International Workshop on Environment and Geoscience. Qingdao China. Website: www.iwegconf.org
- 18-22 JULY 23rd General Meeting of the International Mineralogical Association. Lyon France. Website: www.ima2022.fr

continued on page 21



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	Ta	0.04

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CALENDAR OF EVENTS... *continued from page 20*

18-22 JULY	International Geographic Union Centennial Congress. Paris France. Website: tinyurl.com/bdhdshxtx
30 JULY – 2 AUGUST	12th International Conference on Environmental Catalysis. Osaka Japan. Website: tinyurl.com/2p8b467m
31 JULY - 4 AUGUST	Microscopy and Microanalysis 2022. Portland OR USA. Website: www.microscopy.org/MandM/2022
31 JULY - 5 AUGUST	World Congress of Soil Science 2022. Glasgow UK. Website: www.soils.org.uk/wcss2022
3-5 AUGUST	12th International Conference on Environmental Pollution and Remediation. Prague Czech Republic. Website: icepr.org
6-12 AUGUST	Geoanalysis 2022. Freiberg Germany. Website: tinyurl.com/bdfhr49w
14-18 AUGUST	6th IAGOD Quadrennial Symposium. Dublin Ireland. Website: www.iagod.org/node/116
14-19 AUGUST	Biom mineralization (Gordon Research Conference). Castelldefels Spain. Website: tinyurl.com/5865ckbt
22-26 AUGUST	International Sedimentological Congress. Beijing China. Website: www.isc2022.org.cn/En
23-26 AUGUST	International Symposium on Environmental Geochemistry. Moscow Russia. Website: iseg2022.org
27-30 AUGUST	SEG 2022 Conference. Denver CO USA. Website: tinyurl.com/3m7dnmtv
29 AUGUST - 3 SEPTEMBER	21st Annual Conference of International Association for Mathematical Geosciences. Nancy France. Website: www.iamgconferences.org/iamg2022
5-9 SEPTEMBER	8th World Multidisciplinary Earth Science Symposium. Prague Czech Republic. Website: www.mess-earth.org
7-11 SEPTEMBER	XXII Congress of Carpathian Balkan Geological Association. Plovdiv Bulgaria. cbga2022.geology.bas.bg
11-14 SEPTEMBER	Fifth International Symposium on Ethics of Environmental Health. Budweis Czech Republic. Website: iseeh.org
11-15 SEPTEMBER	IWA World Water Congress & Exhibition. Copenhagen Denmark. Website: worldwatercongress.org
12-15 SEPTEMBER	Earth Mantle Workshop. Toulouse France. Website: emaw2021.sciencesconf.org
12-16 SEPTEMBER	10th International Conference of the International Association of Geomorphologists. Coimbra Portugal. Website: www.icg2022.eu
13-15 SEPTEMBER	14th International Symposium on Nuclear and Environmental Radiochemical Analysis. York UK. Website: tinyurl.com/4mw4n924
21-23 SEPTEMBER	Mongolia Mining 2022. Ulaanbaatar Mongolia. Website: mongolia-mining.com
9-12 OCTOBER	GSA 2022 Annual Meeting. Denver CO USA. Website: tinyurl.com/fuyh2t3z
23-28 OCTOBER	29th International Applied Geochemistry Symposium (IAGS). Viña del Mar Chile. Website: iags2021.cl
17-19 OCTOBER	16th International Congress of the Geological Society of Greece. Patras Greece. Website: gsg2022.gr
27-29 NOVEMBER	Australasian Environmental Isotope Conference. Ballina NSW Australia. Website: www.conferences.com.au/2022aeic
4-9 DECEMBER	American Exploration & Mining Association (AEMA) Annual Meeting. Sparks NV USA. Website: tinyurl.com/ycktxmut
12-16 DECEMBER	AGU Fall Meeting. Chicago IL USA. Website: www.agu.org/Fall-Meeting



The AAG-SGS Student Presentation Prize

The Association of Applied Geochemists, through the support of SGS Mineral Services, awards a prize for the

Best oral presentation by a student at the biannual International Applied Geochemistry Symposium (IAGS)

The intent of this prize is to encourage the presentation of high quality research by students at an International Applied Geochemistry Symposium (IAGS) and provide further incentive to publish the results of the research in the Association's journal, *Geochemistry: Exploration, Environment, Analysis* (GEEA). The winner is determined based on feedback from a group of judges that includes Fellows and Members of the Association. Criteria for judging the presentations include excellence and originality in research design, research execution, interpretation, and the oral presentation itself. Honours, Masters, and Doctoral students are all eligible. The format of the presentation may vary between IAGS.

The Rules

1. The paper must be presented by the student at an IAGS as an oral paper, in the format specified by the IAGS organizing committee.
2. The conference presentation and paper must be largely based on research performed as a student. The student's supervisor or Head of Department may be asked to verify this condition.
3. The decision of the AAG Symposium Co-ordinator (in consultation with a representative from SGS) is final and no correspondence will be entered into.
4. Entry in the competition is automatic for students (but students may elect to "opt out").
5. The detailed criteria and process for assessing the best paper will be determined by the AAG Symposium Co-ordinator in consultation with the AAG Council and the LOC.
6. A paper substantially derived from the material presented at the IAGS and submitted for publication in the Association's journal *Geochemistry: Exploration, Environment, Analysis* within the timeframe specified by the AAG (normally 12 months) will be eligible for the increased value of the prize.

The Prize

1. \$700 CAD from SGS Minerals Services (normally presented to the winner at the end of the relevant IAGS) with a further \$300 CAD from AAG if a paper related to the oral presentation is submitted to GEEA within the nominated time frame after the IAGS;
2. A 2-year membership of the Association, including subscription to GEEA and EXPLORE; and
3. A certificate of recognition.

David Cohen

Chair of Student Prize Committee
University of New South Wales
Email: d.cohen@unsw.edu.au



CALENDAR OF EVENTS... *continued from page 21*

2023

- 29 JANUARY-3 FEBRUARY Winter Conference on Plasma Spectrochemistry. Ljubljana Slovenia. Website: ewcps2021.si
- 13-18 MARCH Australasian Exploration Geoscience Conference. Brisbane Qld Australia. Website: 2023.aegc.com.au
- 19-23 MARCH Minerals, Metals & Materials Society Annual Meeting & Exhibition. San Diego CA USA. Website: www.tms.org/AnnualMeeting/TMS2023
- 26-28 APRIL International Conference on Geographical Information Systems Theory, Applications and Management. Prague Czech Republic. Website: www.gistam.org
- 18-23 JUNE Catchment Science: Interactions of Hydrology, Biology and Geochemistry (Gordon Research Conference). Andover NH USA. Website: tinyurl.com/2p968pxe
- 14-20 JULY 21st INQUA Conference. Rome Italy. Website: inquaroma2023.org
- 16-21 JULY Chemical Oceanography (Gordon Research Conference). Manchester NH USA. Website: tinyurl.com/mu7ybfz6
- 25-27 JULY 6th International Archean Symposium. Perth WA Australia. Website: 6ias.org
- 28 JULY Target 2023: Innovating now for our future. Perth WA Australia. Website: www.aig.org.au/events/target-2022/
- 12-18 AUGUST 5th International Symposium on Environment and Health. Galway Ireland. Website: www.nuigalway.ie/iseh-iceph
- 18-22 AUGUST Water-Rock Interaction WRI-17/ Applied Isotope Geochemistry AIG-14. Sendai Japan. Website: www.wri17.com
- 24-31 AUGUST SEG 2023 Conference: Resourcing the Green Transition. London, England. Website: tinyurl.com/2p8b7mue
- 28 AUGUST-3 SEPTEMBER 8th World Multidisciplinary Earth Science Symposium. Prague Czech Republic. Website: www.mess-earth.org
- 10-15 SEPTEMBER International Meeting on Organic Geochemistry. Montpellier France. Website: eage.org/imog/imog-23

2024

- 25-31 AUGUST 37th International Geological Congress. Busan, Republic of Korea. Website: www.igc2024korea.org



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