**Geochemistry Workshop in ioGAS based on the GSWA Yilgarn Granite Project**

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# Introduction

The Yilgarn Granite Project is another initiative of the Geological Survey of Western Australia. This project is reanalyzing the collection of powders from Cassidy and Champion (2002) using consistent, high quality analytical methods. As with the Barcode Project, these samples were analyzed using the Bureau Veritas laser ablation ICP-MS method. This method uses a Li-borate glass disc to analyze the major elements by conventional XRF, and then uses a chip of the glass disc to measure the trace elements by laser ablation ICP-MS. With this method the majors were reported as weight% of oxides. In the provided ioGAS file, I have modified the format of the data from that provided by GSWA. I have converted the weight% of major element oxides to wt% elements, then alphabetically ordered the elements so that the data format looks like the analytical results exploration geologists would be familiar with (ie 4 acid digest ICP-AES for the major elements and ICP-MS for the trace elements).

Trace elements, particularly the High Field Strength Elements, are sensitive indicators of magmatic processes. The concentrations of the HFSE’s are indicators of magmatic source, pressure, temperature, water content, oxidation state and degree of partial melting. All these parameters contribute to the potential of a fractionating magma to exsolve a hydrothermal fluid phase and create an orebody. Two of the most useful Industry-sponsored research projects in the field of mineral exploration were Bob Loucks’ Porphyry Cu magmatic fertility study and the compilation of Yilgarn granite chemistry by Kevin Cassidy and Dave Champion. Bob Loucks was sponsored by several major companies to compile whole rock geochemistry from porphyry Cu provinces and then document the differences in chemistry between mineralized magmatic rocks and unmineralized rocks. This was an interpretation of the melting and fractionation processes that lead to the formation of porphyry copper systems. The Cassidy and Champion study was a systematic sampling and analysis program of the entire suite of intermediate to felsic intrusive rocks across the Archean Yilgarn Craton. Although they did not specifically look at the association with gold deposits, their data provides the basis for a Loucks-type interpretation of the Archean intrusive chemistry. This tutorial will consider possible links between Archean magmatic chemistry and gold deposits.

In this tutorial we can create a series of plots that are used to identify the effects of fractional crystallization of particular minerals. We can assign the granite chemistry samples into categories defined by the suite of minerals that fractionated to produce a particular trace element signal. This can then be related to P-T-aH2O . Once the Yilgarn Granites data has been examined, I’ll show some plots comparing the chemistry of porphyries from large gold systems with the Yilgarn Granite data.

Archean greenstone-hosted gold deposits are categorized as being “Orogenic” deposits. This implies that the ore fluid was derived via metamorphic dehydration reactions of hydroxyl-bearing minerals within the greenstone belt, and that during that process, sulfur and gold was extracted from the trace amounts occurring through the rock pile. In that scenario, there should be an equal probability of forming gold-bearing orogenic veins anywhere in the greenstone belts containing the same source rocks and deformation styles. However, that is not the case. The gold systems form in clusters (gold camps). Pathfinder elements are spatially zoned at the scale of the gold camps, and small plutons usually of dioritic composition occur within the camps at the center of the metal zonation pattern. The diorites within these gold camps have trace element signatures that are diagnostic of magma compositions with a very high water content. Given the composition of the melts, it is inevitable that those diorites would have exsolved a hydrothermal fluid phase as they cooled and crystallized and hydrothermally altered the volume of rock into which they had intruded. A more plausible explanation for the origin and spatial distribution of greenstone-hosted gold deposits is that rather than being the product of metamorphic dehydration reactions from the entire volume of the greenstone, they were derived from reactions within the volume of hydrothermally altered rock surrounding the diorite intrusive complexes. These alteration cells have pervasive phyllosilicate minerals, carbonates and sulfides with anomalous levels of pathfinders and gold. The implication is that the components of the orogenic gold systems are locally derived, and do not involve metal transport over many kilometers. The diorites associated with the gold systems have distinctive chemical characteristics that can be identified from whole rock analyses.

In any one of these gold camps, it is common to see different styles and ages of mineralization. There are 3 particularly common settings. The first is pervasive, low grade disseminated gold typically at a 50 to 500ppb level within the uppermost portions of the intrusions. The second is ore-grade veins and breccias probably with a direct magmatic contribution in the host rocks above the diorite intrusions, and the third and most common are the classic orogenic style veins. Alteration diagrams from whole rock chemistry showing ratios of major elements based on the stoichiometry of common minerals are consistent with illite-albite-chlorite-carbonate assemblages, even where the rocks are metamorphosed to biotite-amphibole. This shows that the metamorphic reactions liberate water and CO2, but retain the bulk rock composition of the previously altered protolith, rearranged into a new suite of minerals.

A number of geochronology studies have directly sampled orogenic veins, located minerals such as monazite intergrown with gold, and concluded that the orogenic gold event was a different age to the adjacent intrusions and therefore unrelated. These studies have dated the last in a sequence of events that led to the formation of the ore shoots, but have not recognized the full sequence of events.

# Interpretation

The GSWA Yilgarn Granite Project data provided a new set of analyses with a consistent assay scheme and also provided the original metadata and interpretation from Kevin Cassidy and Dave Champion. They devised a classification scheme based on whole rock chemistry and petrology which divided the granites into 5 main categories;

* High Ca
* Low Ca
* Mafic granites
* Syenites
* High Field Strength Enriched (HFSE).

These are the categories provided in the GSWA data;

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The high Ca and low Ca groups are by far the most voluminous. The high Ca group was interpreted to be the product of high pressure melting of a hydrous mafic protolith underplating the crust. The low Ca granites are mid crustal melts. The mafic series granites are similar to the high Ca granites but have a high Mg content at a given SiO2 level. The syenites are alkali-feldspar rich magmas. The HFSE granites have elevated contents of Zr, Th, Nb, LREE’s etc, concentrated via fractional crystallization.

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Loucks (2014) concluded that an elevated Sr/Y ratio was an effective discriminator of ore forming intrusions from barren magmas in porphyry Cu terrains. Richards (2011) interpreted that high water contents at high pressure cause abundant amphibole (± garnet) fractionation but suppression of plagioclase, resulting in increasing Sr/Y. Chiaradia (2015) also related the Sr/Y evolution to crustal thickness. However, this is not a unique argument. Titanite (CaTiSiO5) is a diagnostic mineral in porphyry Cu systems. Chelle-Michou (2015) demonstrated how titanite fractionation caused Nb, a typically incompatible element, to exhibit compatible behaviour, beginning from about 60% SiO2. Olsen (2017) showed that titanite in porphyry systems incorporates Nb, Y, Th, U and all the REE’s, giving all of these elements compatible behaviour with increasing SiO2. Titanite is responsible for the entire Y budget in a porphyry Cu magma, so the Sr/Y signal very sensitive to titanite fractionation. The most plausible explanation for the Sr/Y signal is that it is tracking fractional crystallization of titanite through a window in pressure-temperature-aH2O space where titanite crystallization occurs before plagioclase.

The question of whether Sr/Y is controlled by garnet-amphibole in the source region or titanite fractionation can be tested with the Yilgarn Granites data. Titanite incorporates not only Y, but also Nb, Th and all the REE’s. The ratio of the element abundance in titanite to the element abundance in whole rock is roughly the same for all those elements. The classic “porphyry copper fertility” diagram from Bob Loucks in Sr/Y vs Y. Plots of Sr/Th vs Th or Sr/Nb vs Nb look just the same! This would not be the case if the Y signal in porphyry Cu magmas was controlled by garnet and hornblende in the source region. We can conclude that the size and endowment of porphyry Cu systems is indicated in part by the extent of titanite fractionation. Whether the control on Y is exerted by titanite or garnet does not really change the conclusions. Plagioclase melting is strongly dependent on both pressure and water content, so titanite crystallization prior to plagioclase is still nevertheless an indicator of a high pressure hydrous source region.

The “mafic” series granitoids through to high Ca granites in the Archean share this same Sr/Y signal with porphyry Cu magmas. In modern volcanic arcs, intrusions associated with porphyry Cu mineralization typically have SiO2 around 62 to 70% SiO2 and Sr/Y from 40 to 120. The high Sr/Y ratio is much more widespread in Archean rocks than in modern arc magmas. There is a serious research topic to consider here; why is it that the Archean subcontinental lithospheric mantle was so widely hydrated? The Sr/Y vs SiO2 plot for the Yilgarn granites is almost bimodal. The Archean granites could be divided into 2 classes based on this plot.

As an aside, the mafic series diorites were so named because they have a high Mg/(Mg+Fe) ratio. The plot below compares the Yilgarn Granites data on the left with a data set from the Vizcachitas porphyry Cu deposit on the right. The Cu-related intrusions at Vizcachitas are the red to pink to magenta groups. These are typical of porphyries in the El Teniente belt. Note the porphyry Cu magmas have the same Mg/(Mg+Fe) as the Yilgarn mafic suite.

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A plot of SiO2 versus Eu\* effectively subdivides the granite compositions in the same way as Sr/Y does. With few exceptions, rocks with Eu\* > 0.8 have Sr/Y > 25. The lack of plagioclase fractionation and the incorporation of Y into titanite are the controllers for the Sr/Y signature in these rocks. Note that on the basis of the Eu\* and Sr/Y signature, some of the high Ca group plots with the mafic series, and the rest of the high Ca group has fractionated plagioclase in the same way as the low Ca group.

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Another very distinctive characteristic that the mafic series intrusions have in common with porphyry Cu magmas is the V/Sc ratio. Porphyry Cu magmas develop in a pressure-temperature-aH2O window where hornblende crystallization occurs before magnetite. V becomes less compatible in silicates as magmas become more oxidized, so hornblende crystallization removes Sc from the melt at a faster rate than it removes V. The opposite is true at lower pressure and lower H2O, where magnetite removes V faster than Sc. Therefore the V/Sc plot shows a similar pattern to the Sr/Y plot, but related to different minerals. Thus a first-pass subdivision of magma types should be made on the basis of whether the melts have fractionated hornblende + titanite or plagioclase + magnetite.

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Almost all rocks with SiO2<70% have Zr/Hf around 36. Zircons generally start crystallizing around 750 to 800 degrees, when magmas have reached about 70% SiO2. Hafnium substitutes into zircons, but Zr/Hf in the melt is always a little lower than Zr/Hf in zircons. If zircons crystallize and are separated from the remaining melt, then the Zr/Hf ratio in the remaining melt decreases. The effect of fractional crystallization of zircons in some of the low Ca and in the high HFSE granites can be seen in the SiO2 versus Zr/Hf plot.

Alkalic magmas typically have higher Zr/Hf. The granites with less than 70% SiO2 should have Zr/Hf ratios around 36:1. The scatter in this ratio is greater than I would expect, and I attribute this to the precision obtained using a single laser ablation spot.

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The Zr versus Hf plots above compares the Yilgarn granites data (left) with another Yilgarn data set (right) with over 20,000 analyses. The plot on the left is from Li borate fusion, so these analyses are likely to be close to a total digest. The plot on the right is from 4 acid digest, so probably not all of the zircons were totally dissolved. The plot on the left is more accurate, but the plot on the right has higher precision. I suspect the reason for the lower precision in the Yilgarn Granites data is that these were measured with laser ablation ICP-MS on chips of the borate glass, but measured just one laser spot per chip.

Alkalic magmas are more widespread in the Yilgarn than recognized in the literature or recognized by mining companies. Within andesitic to rhyolitic rock compositions, most of the Ca in a rock is hosted by plagioclase, almost all the Na and K is hosted by feldspars, and most all the Al is hosted by feldspars. On a molar basis, Ca+Na+K is roughly equal to Al. The Ca content *decreases* with increasing SiO2 content as calcic plagioclase crystallizes, but K and Na contents increase with increasing SiO2, creating a crossover between Ca and K + Na. There is no consistent or unique definition of calc-alkaline versus alkaline series, but the distinction is based on the ratio of (Na+K)/(Ca+Na+K) ***at a given SiO2 level***. Alkali feldspars have a lower melting point than calcic feldspar. The formation of alkalic magmas is attributed to a very low degree of partial melting of the source rock, with somewhere in the order of 5% of the source rock going into the magma melt. Definitions of alkalic compositions based on Ca, K, Na and Si are not very useful because these signatures will not be preserved during hydrothermal alteration. One distinctive characteristic is a higher Zr/Hf ratio. My hypothesis of the high Zr/Hf ratio in strongly alkalic rocks (up to 50) is that these rocks have much higher Zr in Si-undersaturated melts, they crystallize ZrO2 (baddeleyite) before zircons.

Alkaline magmas also have high a Ti content as well as phosphorus and light rare earth elements. They are elevated in Sr and Ba. The Sr component of plagioclase is linked to Na, and Ba also enters the melt with K feldspar, therefore high Sr and Ba could be attained in the early stages of alkali felspar melting.

Since titanite is a sink for most of the HFSE’s, fractionation of this mineral leads to suppressed levels of HFSE’s in porphyry Cu magmas. They typically have Th values around 2 to 4ppm, Nb around 2 to 4ppm, and Ce around 20 to 40 ppm. These ranges are very similar to the HFSE’s in the mafic series intrusions.

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In the following series of plots, I have changed the colour scheme and simplified the classification into Hornblende Diorite (high pressure hydrous melts), Potassic granites (low pressure crustal melts), Fractionated Potassic Granite and Alkalic Suite. The latter two were defined mainly based on the Zr/Hf ratio. The former two were defined primarily from V/Sc and Sr/Y. The weakness with this classification scheme is that it relies on having high precision Hf and Zr analyses, and Sr is likely to be mobile during hydrothermal alteration.

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With this modified classification, note how the Ti vs Th, Ce and Nb plots are more or less bimodal between the hornblende diorite and potassic granite types. The Ti vs P plot begins to hint at the high phosphorous character of the alkalic suite.

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The following table provides some guidelines for making these classifications.



If you are dealing with 4 acid digest ICP data and don’t have SiO2 or REE analyses, then try these plots as an alternative.

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Although there is a continuum between the compositions of the hornblende diorites and alkalic magmas, in the Eastern Goldfields of the Yilgarn Craton they have distinctly different geological settings and timing. In the Kalgoorlie region the cessation of extrusive volcanism coincided with a deformation event which lead to uplift and erosion of the greenstone sequence and deposition of epiclastic sediments above an erosional unconformity. The hornblende diorites were emplaced prior to this event. However all of the intrusions emplaced within the epiclastic sediments have an alkalic signature. The potassic granites came later still. The classifications of the granite petrogenesis here relies on V, Sc, Sr, Y, Zr and Hf and REE’s to decipher mineral fractionation. The following 2 plots show how this is manifested in the alkali elements and Ca.

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The significance of high Sr/Y and high V/Sc is that these are very hydrous melts. However that is only part of the story. The really important ingredient in the intrusions associated with gold mineralization is a high S content. A metasomatized mantle source is implicated in this. In the hornblende diorites and alkalic magmas, a proxy for this is the Ba content. In these rocks, a threshold of >1000ppm Ba is significant. The crustal melts are already potassium-rich hence high Ba. A few crustal melts are linked to mineralization, and these tend to be very highly fractionated (analogous to reduced intrusion-related gold systems).

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There are more magma types within this data that are perhaps represented by just a small number of data points, but they are intrusive types that are not linked to gold systems. One other plot worth looking at in other types of mineral systems is Rb vs K. In most unaltered igneous rocks, there is a strong linear correlation between K and Rb. Rb substitutes directly for K in common silicates. However it is somewhat incompatible, so with fractionation in potassic granites, the Rb/K ratio increases. To put this into context, the Tasmanian Tin Granites at 4% K would have 400 to 800ppm Rb. Lithium-cesium-tantalum pegmatites evolve to much higher levels. The increasing Rb/K ratio is an indicator of fractionation of K feldspar.

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# Signatures of Gold-related Intrusive complexes.

The following library of case studies overlays the chemistry of porphyries that are at the center of a number of major (+2 million ounce) gold systems. In the following figures, the small grey points displayed on the geochemical fractionation diagrams are the Yilgarn Granites data. The larger coloured points are from geochemical analyses of intrusions within the gold systems.

**Wallaby**

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This data is from the Wallaby deposit in the Laverton district. Wallaby has past production plus resources of around 10 million ounces. Wallaby contains a diverse range of intrusion compositions, including true syenites, monzonites, lamprophyres and carbonatites. The alkalic magmas have Zr/Hf ratios up to 55, V/Sc from 7 to 10 and high Sr/Y. Note however that the Sr/Y signature is different to the typical hornblende diorite. In the alkalic magmas, BOTH Sr and Y are relatively high. This is different to both the hornblende diorites and the potassic granites.

**St Ives, Beta Porphyry**

The Beta Porphyry at St Ives has somewhere in the vicinity of 1 billion tonnes with a median gold grade of 0.12g/t and a mean grade of 0.37g/t (ie, the grade is very uniformly distributed. There are several intrusions in the St Ives camp with chemistry and gold grades like this. The signature of the Beta Porphyry is remarkably like modern porphyry Cu magmas, with the exception that it has released a CO2 rich fluid rather than a saline fluid. Sr/Y from 40 to 100, V/Sc mostly from 7 to 10, perhaps also including a few incorrectly logged rocks. These data are quite old, and I am suspicious that Hf has under-reported. The quality of Zr analyses and especially Hf analyses has vastly improved with modern ICP-MS.

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**Case Study 3**

This is a system with about 6 million ounces of historic production. These data show 2 different populations, one with 55 to 62% SiO2, and the other with 66 to 72%. The intermediate group has high Sr AND relatively high Y and resembles the Wallaby alkalic magmas in that regard. Also, all of these rocks have unusually high Zr/Hf, and I am very confident about the quality of these analyses. Note also the high P content, especially in the intermediate composition group. These intrusions have very consistent Au levels around 50 to 100ppb, but the economic ore shoots are all in shear zones above the intrusion. In terms of the chemistry, this is a classic alkalic signature.

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**Case Study 4, Granny Smith**

These are analyses of intrusions from the Granny Smith region in Western Australia. Granny Smith has historic production of around 2 million ounces. This plot shows 2 different compositional groups; one looks like a conventional hornblende diorite, and the other is alkalic. Note where the alkalic rocks plot. They have a high Sr/Y ratio, but unusually high Y, like Wallaby and Case 3. The alkalic intrusion also has very high Zr/Hf, very high V/Sc and very high P. This is part of an intrusive complex that extends to the south, and the porphyry intrusions within the Sunrise Dam deposit 30km south of Granny Smith are probably part of this same magmatic event.

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**Case Study 5**

This data is from a deposit with around 10 million ounces of production + resources. These rocks are distinctly alkalic. They have exceptionally high V/Sc, high Sr AND Y very high Zr/Hf and very high P. All these alkalic examples plot in a distinctive part of the “adakite” diagram.

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**Summary**

Archean hornblende diorites are remarkably similar to magmas associated with porphyry Cu deposits, with one critical exception; the archean magmas are associated with CO2-rich fluids, and the Cu magmas are associated with saline fluids. These melts are generated in very different tectonic settings, but with similar P-T-aH2O conditions. There is a continuum of compositions between the hornblende diorites and magmas that are more alkalic in character, right through to syenites and lamprophyres. This is the association described by Smithies et al (2018), who referred to these rocks as sanukitoids. I have used a terminology that is more aligned with the definitions applied in porphyry Cu systems. It seems that calc-alkaline magmas fractionate titanite, whereas alkaline magmas do not. I suspect that the controlling factor is the (K+Na)/(Ca+K+Na) ratio, which in turn reflects the degree of partial melting. On this basis, Archean granites could be categorized as high pressure melting to derive calc-alkaline or alkaline melts, or low pressure melting to derive potassic granites. Thus the differences in chemistry reflect the pressure and water content, degree of partial melting and extent of fractional crystallization.

There are 3 different types of magmas associated with gold systems, and within the eastern Goldfields of the Yilgarn Craton, these represent 3 different ages. Some deposits are associated with classic hornblende diorites. This magma type is really common among the Archean granitoids, but not that well represented in the mineralized camps. However examples do include particularly well endowed systems, eg St Ives, Jundee. The hornblende feldspar porphyry dykes with the Kalgoorlie Super Pit probably belong to this group as well.

There is a small number of gold systems related to highly fractionated potassic granites. These are quite rare. Examples include the Lone Hand Monzogranite at Ora Banda, and some phases of the Liberty Granodiorite at Mt Pleasant.

Alkalic magmas are volumetrically minor and make up a small percentage of the Archean granitoids. However they are very strongly represented among the mineralized systems. Examples include Wallaby, the Granny Smith to Sunrise Dam corridor, the Agnew district, Kanowna Belle and the Binduli suite on the margins of the Kurrawang epiclastic basin.

In terms of the magma chemistry, there is no magic bullet that identifies well endowed intrusives. The magic ingredient for gold fertility is sulfur! The feature that works in an exploration context is that the magmatic hydrothermal sulfur around the intrusions can be detected as a footprint of anomalous Bi-Te +/- Mo.

Bob Loucks concluded that under the right P-T conditions, any andesitic magma could fractionate to form a porphyry copper system, but gold-bearing porphyries required a metasomatized mantle source. The bias towards alkalic magmas in Archean systems also reflects this process.

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