

The role of geochemistry in understanding mineral systems

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SUMMARY

The mineral system concept is a valuable framework to use for mineral exploration because it allows the user to interpret their data with more flexibility than for traditional ore deposit models. Better context is provided by a well constructed mineral deposit model because fundamental processes can be adapted to a broad range of systems.

Geochemistry adds much needed detail to any mineral deposit model in three main areas: (1) immobile element geochemistry to better constrain lithological units and define a more detailed stratigraphy, (2) alteration geochemistry to quantify mass balance leading to a better understanding of hydrothermal fluid flow and potential trap sites, and (3) metal enrichment signatures and how they vary across a mineral system so that exploration can be focussed on those parts of the mineral system that have the highest likelihood of exploration success.

INTRODUCTION

The mineral systems concept (McCuaig et al., 2010) is a helpful framework into which we can place our exploration data, interrogate it and erect new hypotheses for testing. Correctly used, it is more flexible than traditional ore deposit models which have more fixed assumptions, and it also encompasses a larger volume of rock, taking into account energy inputs, metal source regions, flow paths, trap sites and spent fluid paths.

Whole-rock geochemistry is a cheap and widely available tool that can be used to advance understanding of a mineral system in three major ways:

1. Immobile element lithogeochemistry to constrain stratigraphy,
2. Alteration geochemistry to quantify mass balance changes along hydrothermal flow paths, and
3. Metal enrichment signatures related to mineralisation.

Each of these areas of investigation can be applied at any scale, and there are procedures specific to each of them. Following the mineral systems approach makes the explorer more mindful of the importance of scale when interpreting geochemical and other data. It also encourages that explorer to try and fit “the pieces of the puzzle” into a coherent whole, and in so doing increases the likelihood that sensible exploration targets will be tested in a logical fashion.

IMMOBILE ELEMENT LITHOGEOCHEMISTRY

In any hydrothermal mineral system, there is widespread mass transfer meaning that, at best, mobile elements (including most

major elements) will only serve as a rough guide to original rock compositions. The more intense the alteration, the more pronounced this problem becomes. Apart from rare cases of extreme alteration, “immobile” elements (Figure 1f) are neither added to, or removed from, the rock mass. Therefore immobile element ratios remain constant for each rock type. Immobile element ratios can be used to identify sedimentary packages of the same provenance and they are particularly powerful for discriminating different igneous rocks. Two different types of immobile element ratio are important:

1. Incompatible / Incompatible Element Ratio (e.g. Zr/Th to discriminate different magma series), and
2. Compatible / Incompatible Element Ratio (e.g. Ti/Zr to discriminate different degrees of fractional crystallisation within a magma series)

In cases of extreme alteration, where some of the normally immobile elements have undergone mass transfer, there is usually a subset of immobile elements that have remained fixed and still have constant inter-element ratios.

In the Panorama VHMS mineral system, the Ti/Zr ratio (higher values are more mafic) is a very helpful check on the rock units that have been mapped, but the Zr/Th and Th/Yb ratios resolve discrete magma series in the volcanic pile (Figure 1) that could not be recognised without geochemistry. For a VHMS mineral system, breaks in volcanic activity are potential host horizons, so recognising these breaks is very important for a better understanding of stratigraphy, and through that, the mineral system. The reason that incompatible-immobile element pairs can be used to distinguish different batches of magma is that these elements stay in the melt rather than crystallising in phenocryst phases. Therefore, as fractional crystallisation proceeds, the initial incompatible-immobile element ratios of the melt are preserved and can be used to fingerprint rocks that belong to it.

ALTERATION GEOCHEMISTRY

An advanced understanding of alteration in a mineral system is generally not possible until starting compositions have been constrained through adequately understanding the host strata. Mass balance studies (e.g. Gresens, 1967; McLean and Barrett, 1993) can quantify how much of each mobile element has been added and lost throughout the mineral system so long as the starting compositions are adequately constrained. A quicker and very effective approach used by Halley (2016) is to model mineralogy throughout a mineral system using a suite of geochemical plots appropriate to that mineral system and that highlight key alteration processes. The keys to using this approach are to plot alteration minerals on those graphs and have the knowledge to discern alteration-related processes from lithological ones. Both are potential drivers of geochemical trends on mineralogical plots.

Both approaches are effective in mapping important aspects of the Panorama mineral system. Brauhart et al. (2001) made mass balance calculations for major and selected trace elements following the methods of McLean and Barrett (1993). Magnesium is added to chlorite-quartz altered rocks near the base of the volcanic pile and in discordant corridors underneath the prospects and deposits (interpreted as hydrothermal discharge zones; Figure 2a). Copper is strongly depleted (1-2 ppm Cu in mafic and intermediate rock) in the same zones as well as in feldspar-bearing rock from high temperature alteration zones at the bottom of the volcanic pile (Figure 2b). A simple Na/Al versus K/Al molar ratio plot (Figure 2c) is very effective at demarcating major alteration zones and a zone of Na-enrichment near the base of the volcanic pile (Figure 2d).

At Panorama, alteration mapping is interpreted to reflect a seawater dominated convective hydrothermal alteration system and that map is consistent with whole-rock geochemistry data. Alteration temperatures are interpreted to increase across semi-conformable alteration zones that overlie a large subvolcanic intrusion; the Strelley Granite. Focussed zones of high-temperature hydrothermal discharge are interpreted to have followed discordant zones of chlorite-quartz alteration that are mapped by Mg mass transfer (Figure 2a) and combined low Na/Al and K/Al molar ratios (Figure 2d). A map of Cu mass transfer suggests that the northern part of the district around Sulphur Springs and Kangaroo Caves may be more fertile based on the amount of metal leached from the footwall.

METAL SIGNATURE

Multielement geochemistry is our primary tool for understanding the combination of elements that are enriched in a body of mineralisation and give it its “multielement signature”. That pattern of element enrichment is more subtly expressed in the fresh rock halo to mineralisation as well as dispersed by weathering and erosion in weathered rock. Understanding the zonation of metal signature in fresh rock is one of the keys to understanding metal distribution throughout a mineral system and for interpreting its modified expression in the regolith.

One of the best tools for isolating metal associations related to mineralisation is by the expert use of Principal Component Analysis (PCA). It can be used at all scales from a portion of a mineral deposit to data covering an entire mineral system and on data types including drill, rock chip, soil and stream sediment samples. Most of the variation in a multielement dataset is captured in the first handful of principal components by PCA. In drill data from a mineral deposit, the main metal signature will feature on PC1, whereas it is likely to be a much more subtle feature on a lower order PCs like PC4 or PC5 in regional stream sediment data. As for mineral systems analysis in general, it is important to subset data for PCA so that metal signatures are understood over a range of different scales.

The OSNACA transform (Brauhart et al., 2017) provides a framework in which any metal enrichment can be mapped in Magmato-Hydrothermal Space (MH-Space) relative to a global database of ore samples (Figure 3). A key finding of the work by Brauhart et al. (2017) is that ore deposits have a range of signatures and occupy a discrete volume within MH-Space. Data for individual deposits overlap to define a volume for each

ore deposit class, and all the deposit classes combined map the architecture of MH-Space (Figure 3). Again, it is possible to interrogate data at all scales from within an individual deposit, through camp and deposit class scale to all of MH-Space. A fruitful area of future research is likely to be mapping subtle variations in metal signature within deposits and across mining camps and the OSNACA-transform is an ideal tool to do this work. Such work should lead to a better understanding of how mineral systems work and where economic concentrations of metal are most likely to be found in those systems.

CONCLUSION

Multielement geochemistry can prove overwhelming in both its depth (number of samples) and its breadth (number of elements). However, there are well proven tools that explorers can use with these data to:

1. Better discriminate strata across an entire mineral system. From a more detailed understanding of stratigraphy comes better structural interpretations.
2. Quantify mass changes associated with hydrothermal alteration and constrain the likely mineralogy of that alteration. To understanding the 4-D architecture of an alteration system is to understand the 4-D architecture of the hydrothermal fluid flow.
3. Gain a detailed understanding of the multielement nature of metal enrichment (signature), and more importantly, spatial variations in that signature across the mineral system. Both intra- and inter-deposit variations are important.

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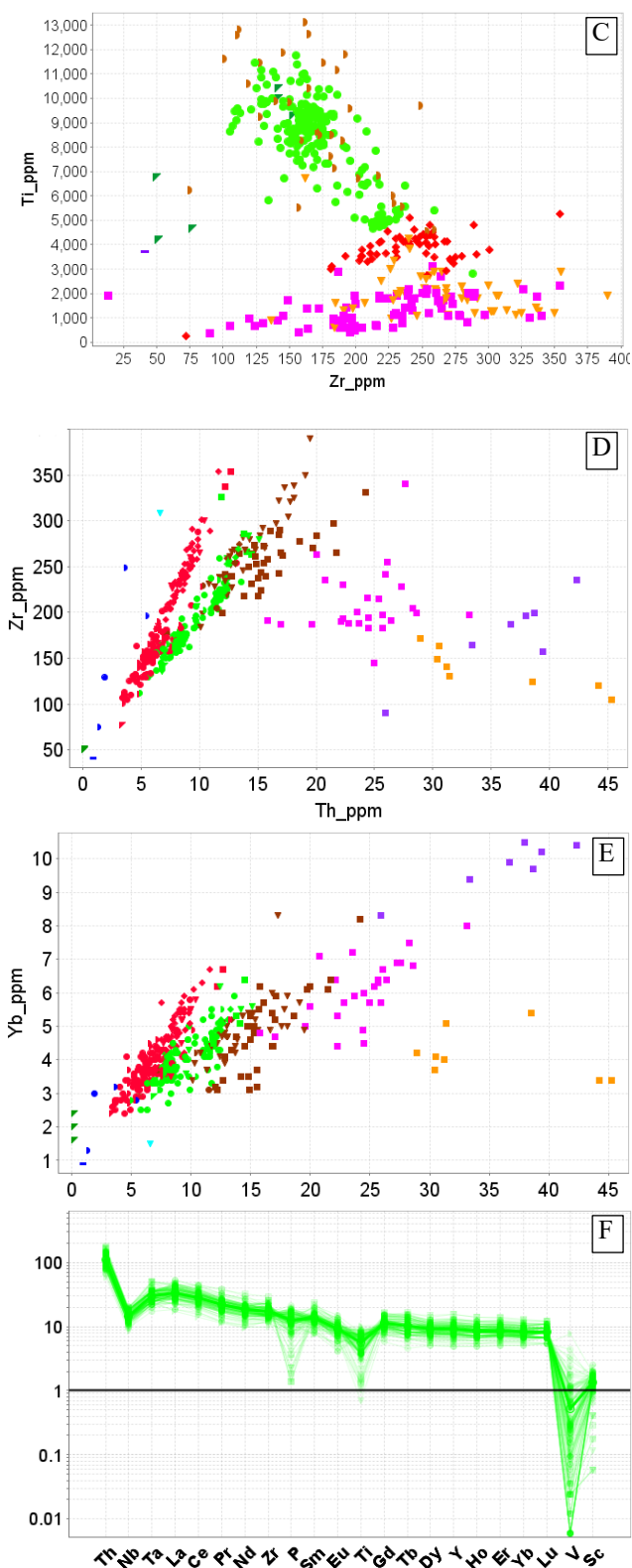
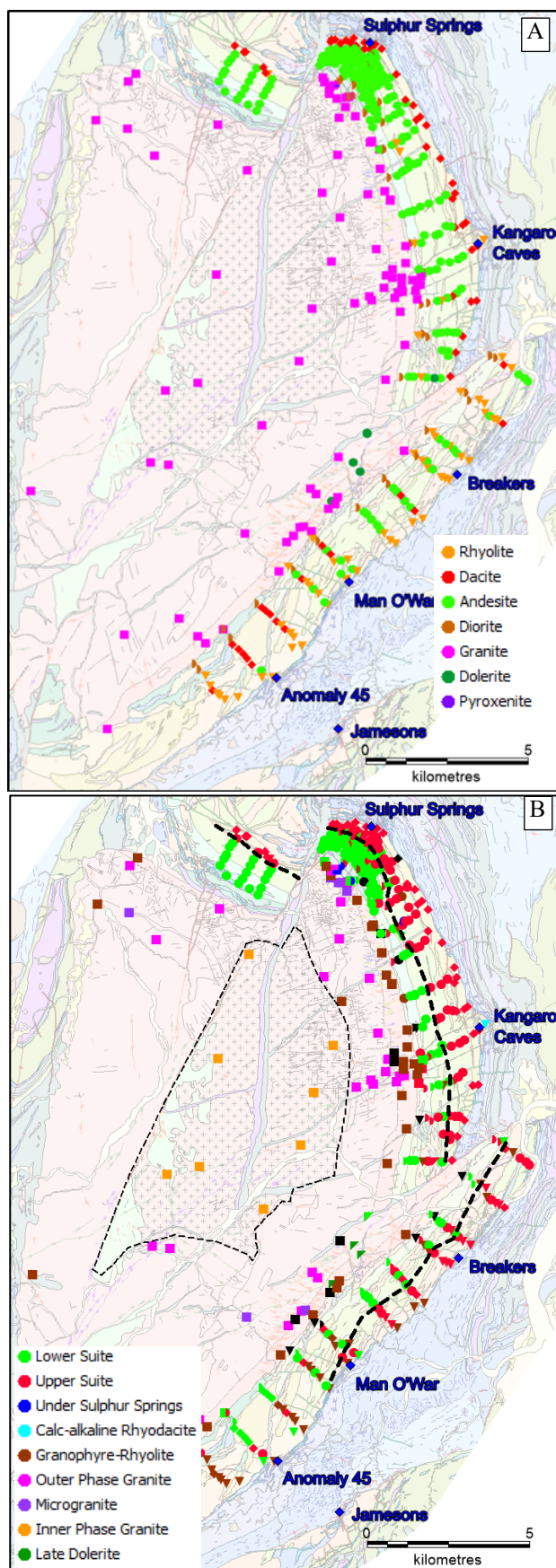


Figure 1. Panorama VHMS District (A) rock samples classified according to composition, (B) rock samples classified according to magma series, (C) Zr-Ti plot with same legend as 1a, (D) Th-Zr plot with same legend as 1b, (E) Th-Yb plot with same legend as 1b, (F) Extended primitive mantle normalised trace element diagram showing lower suite volcanic samples.

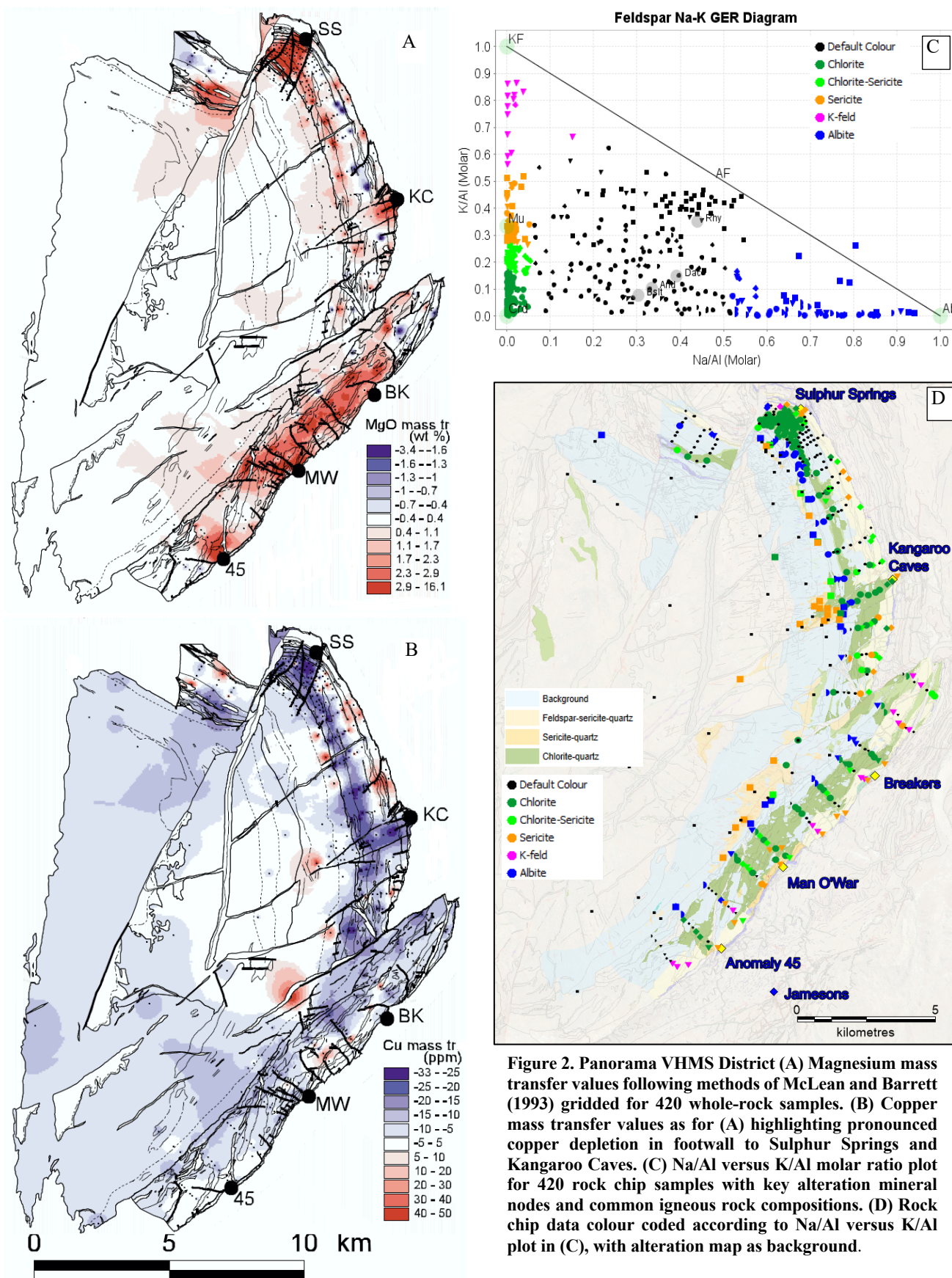


Figure 2. Panorama VHMS District (A) Magnesium mass transfer values following methods of McLean and Barrett (1993) gridded for 420 whole-rock samples. (B) Copper mass transfer values as for (A) highlighting pronounced copper depletion in footwall to Sulphur Springs and Kangaroo Caves. (C) Na/Al versus K/Al molar ratio plot for 420 rock chip samples with key alteration mineral nodes and common igneous rock compositions. (D) Rock chip data colour coded according to Na/Al versus K/Al plot in (C), with alteration map as background.

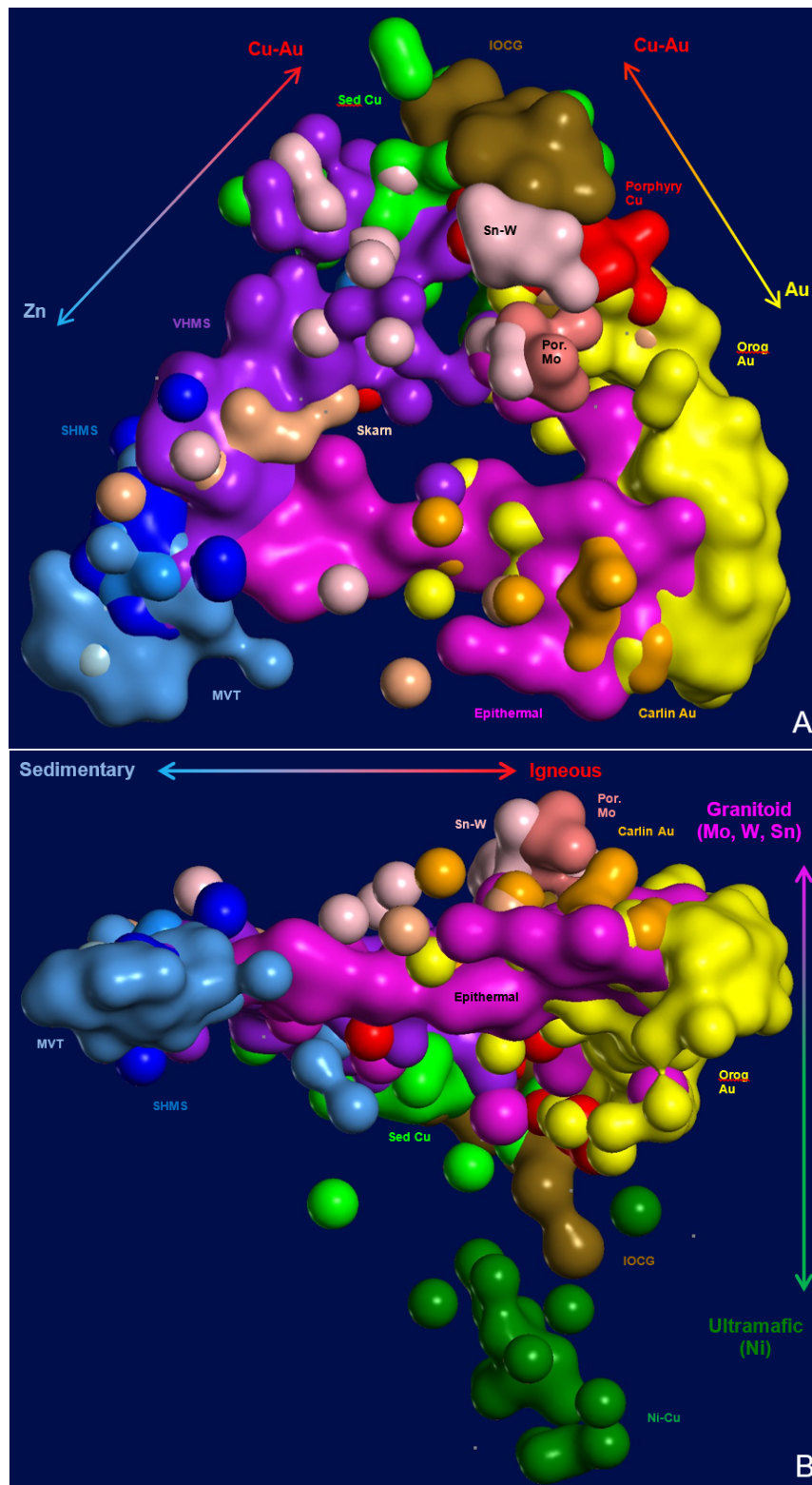


Figure 3. Three dimensional views of MH-Space for 573 OSNACA-transformed ore deposit samples. (A) Looking down on main hydrothermal plane, and (B) side on to main hydrothermal plane with Ni-Cu-PGE below and granitoid mineralisation above.