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The Role of Geochemistry in Mineral Systems

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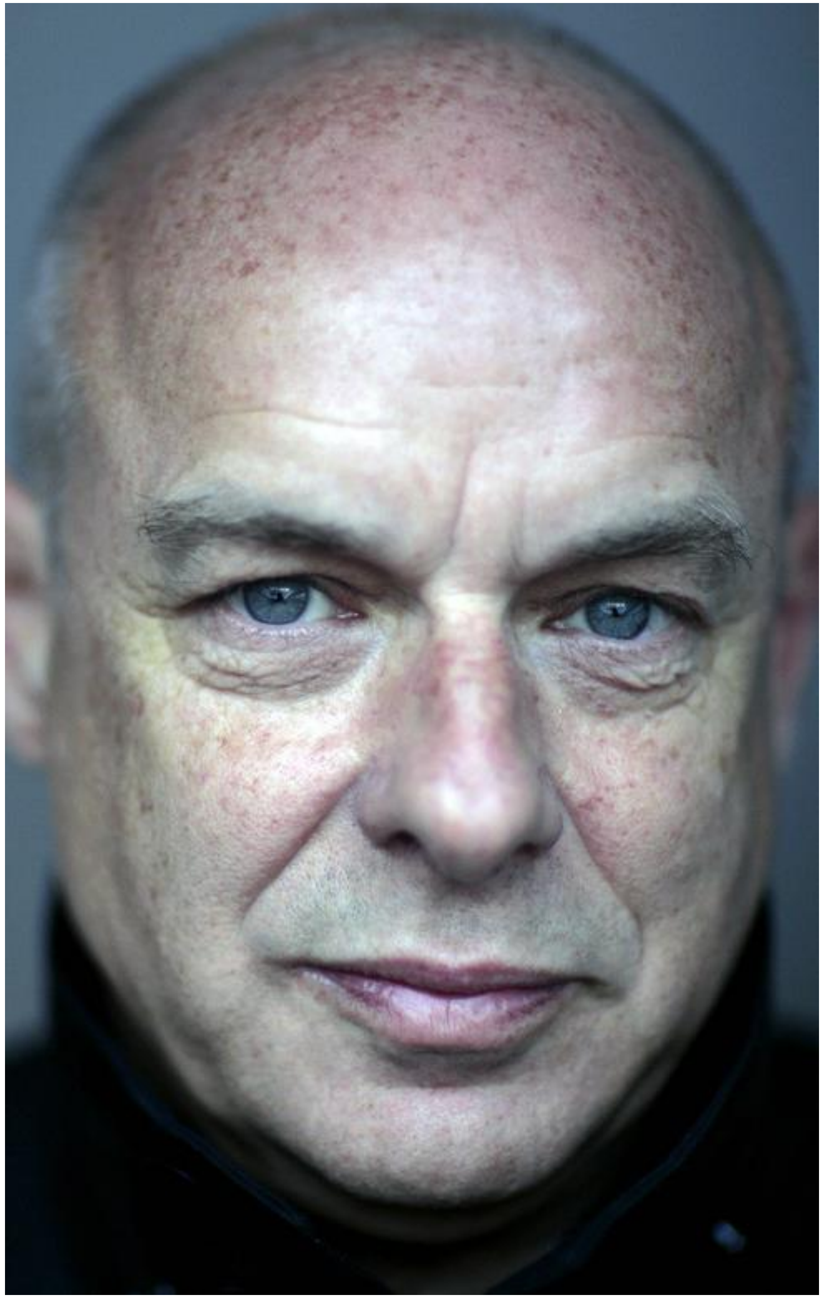
Setting out to be Creative

"If you want to end up somewhere different, you need to start somewhere different"

Brian Eno

Music Producer

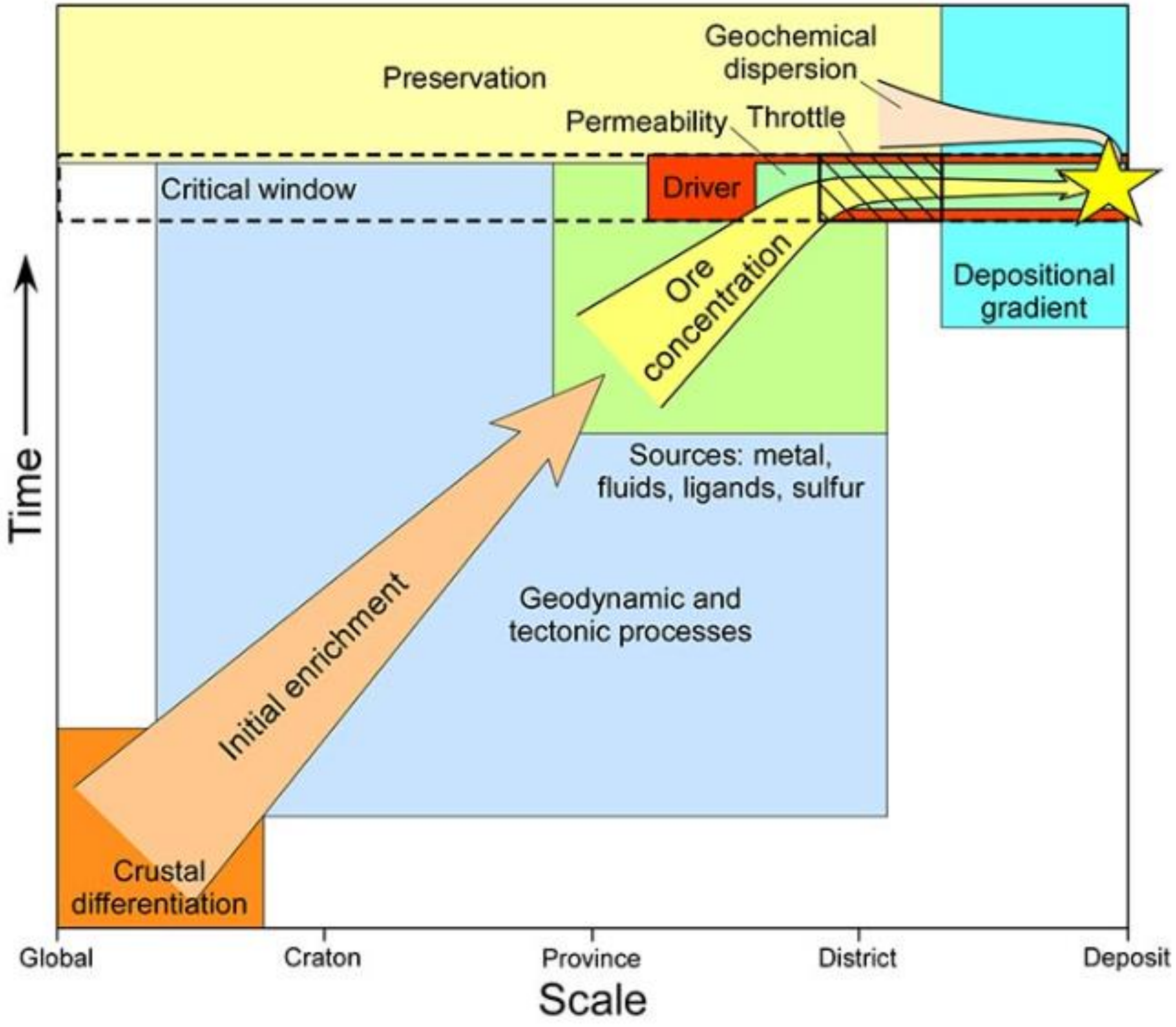


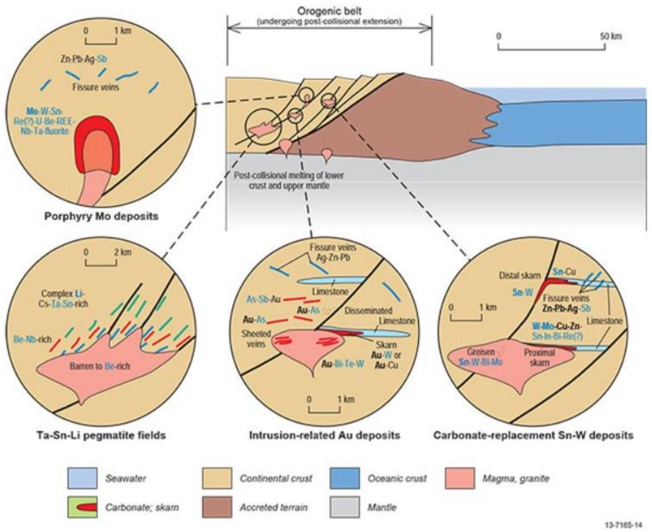
Take-Home Messages

In Mineral Exploration there are THREE main things that whole-rock geochemistry can help us with

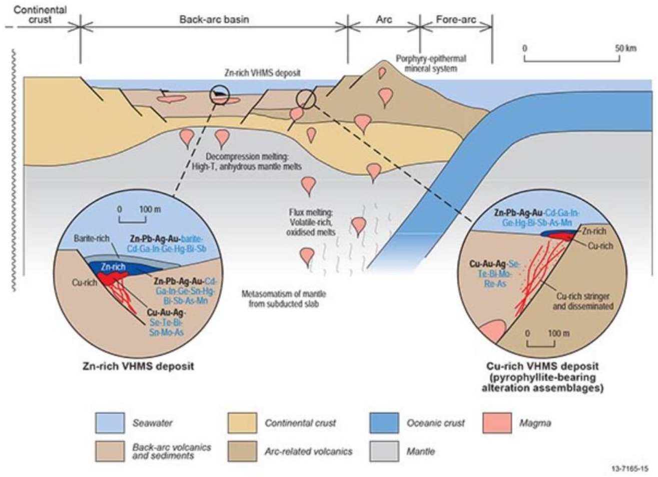
1. **Lithology (Mostly Immobile Element Geochemistry)**
2. **Alteration (All About Mineralogy)**
3. **Metal Signatures (Direct Detection of Mineralisation With Multielement Geochemistry)**

Mineral Systems = Context





Granite-related: ga.gov.au



VHMS: ga.gov.au

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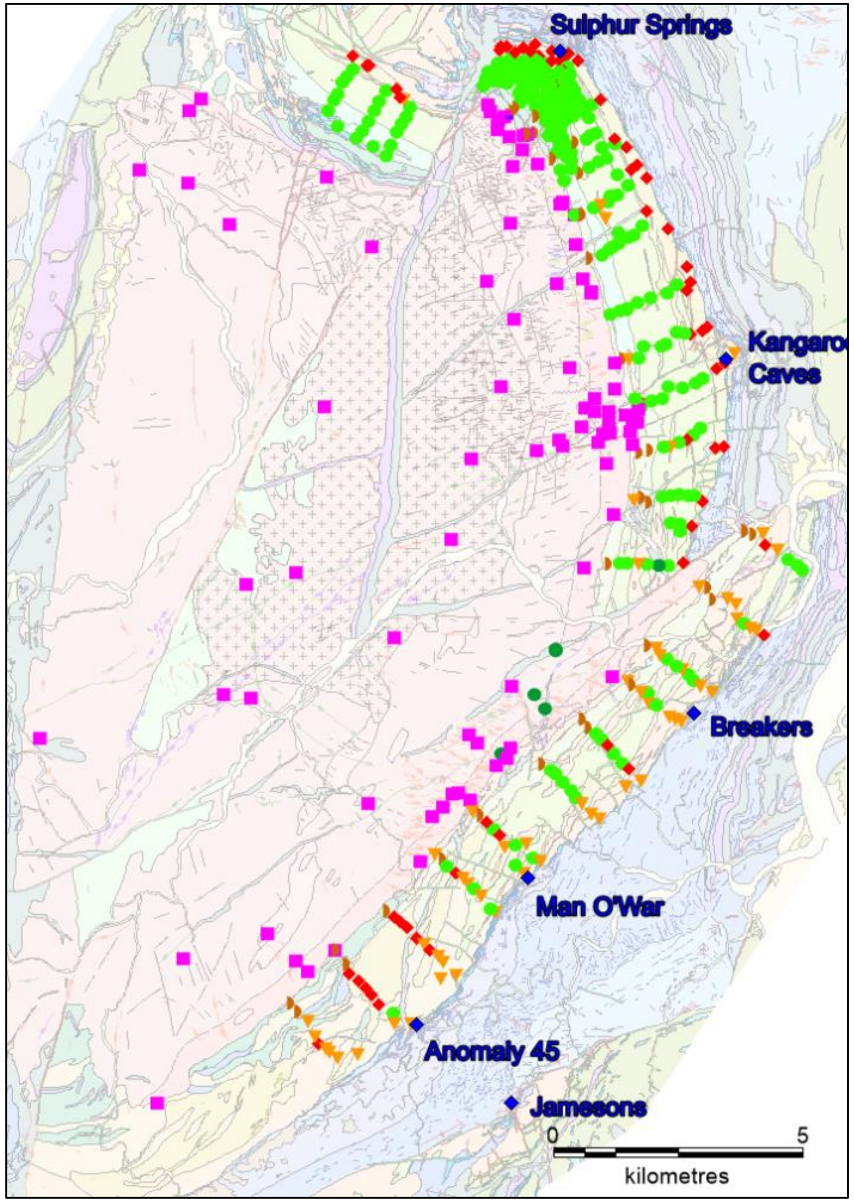
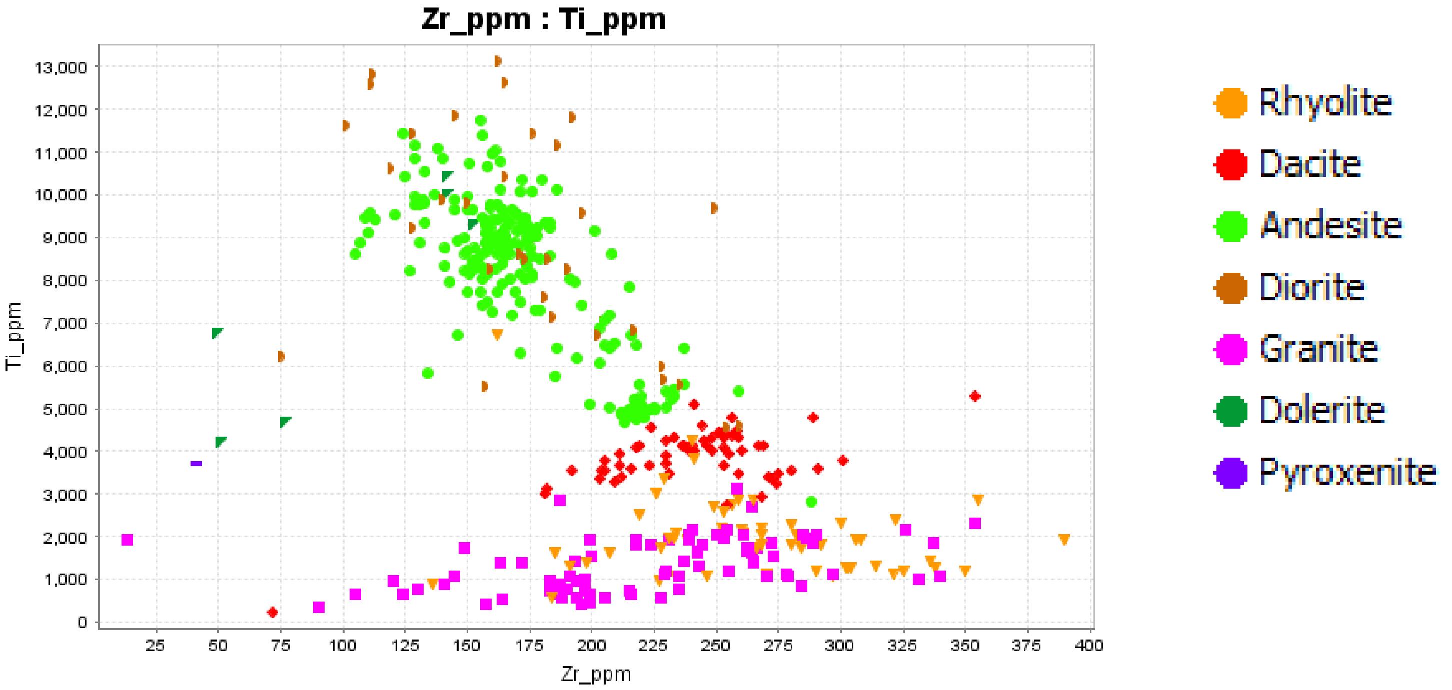
1. Immobile Element Geochemistry

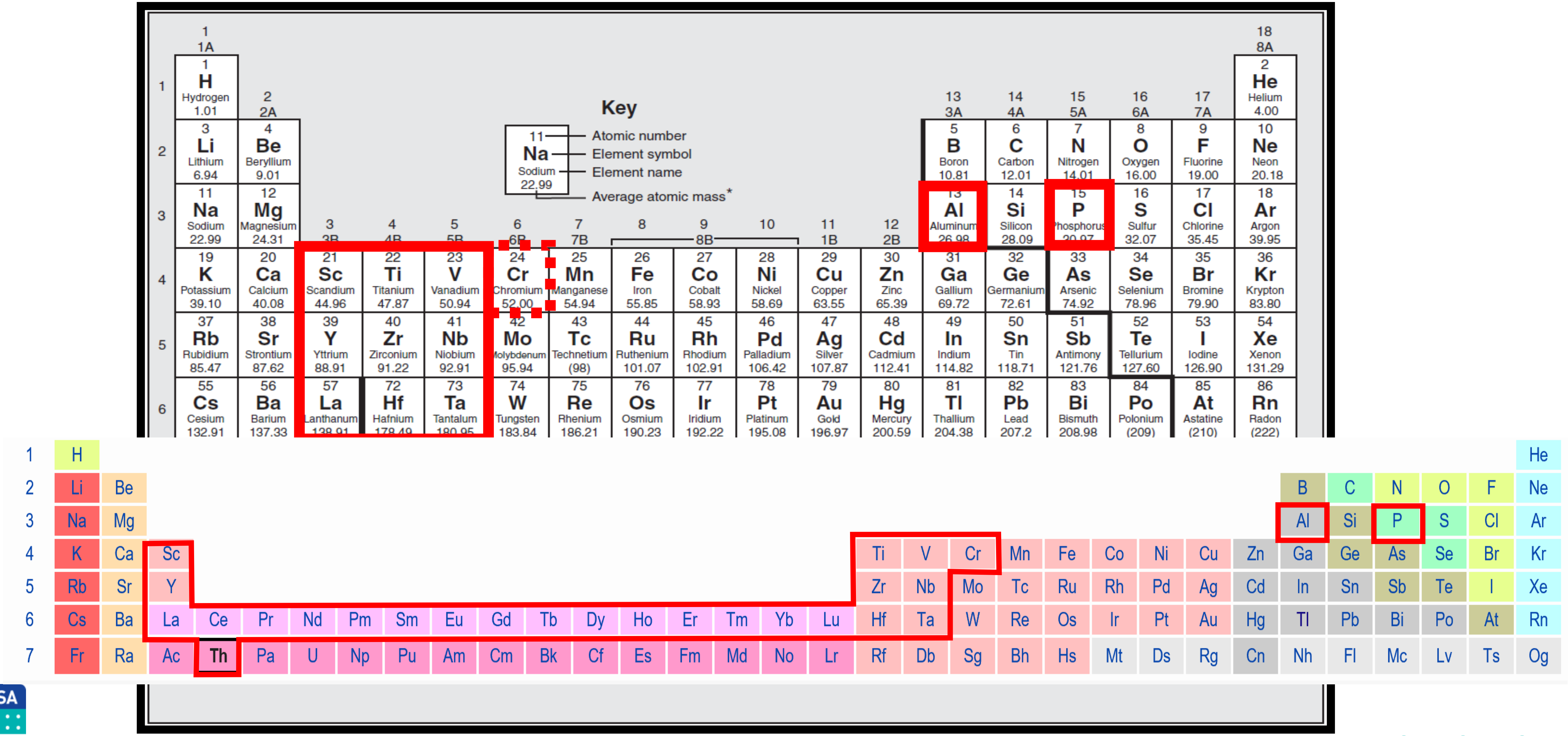
Immobile Element RATIOS Define Rock Types





- Immobile elements neither enter, nor leave a rock mass during alteration or weathering
- Concentrations may change, ratios remain constant
- Key elements include Th, Nb, REE, Zr, Ti and Sc

Immobile Elements



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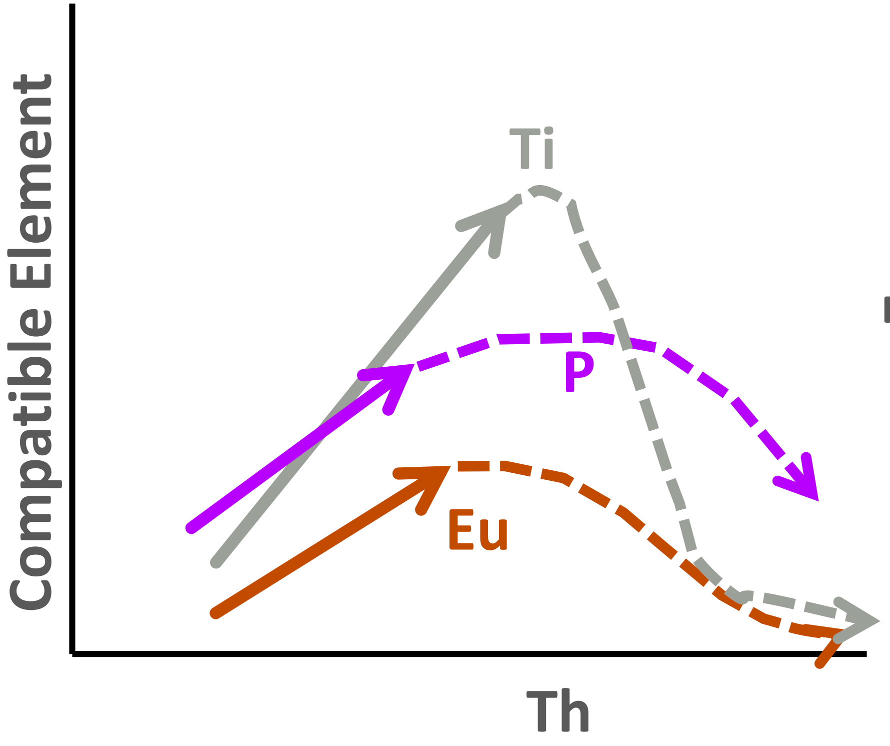
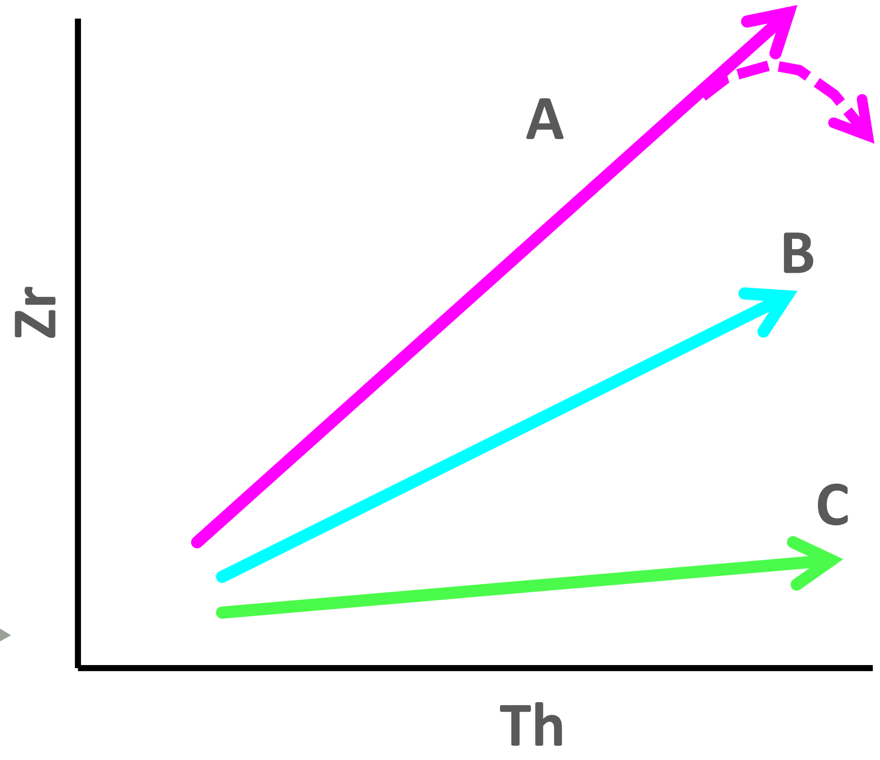
Immobile-Incompatible Element Classification

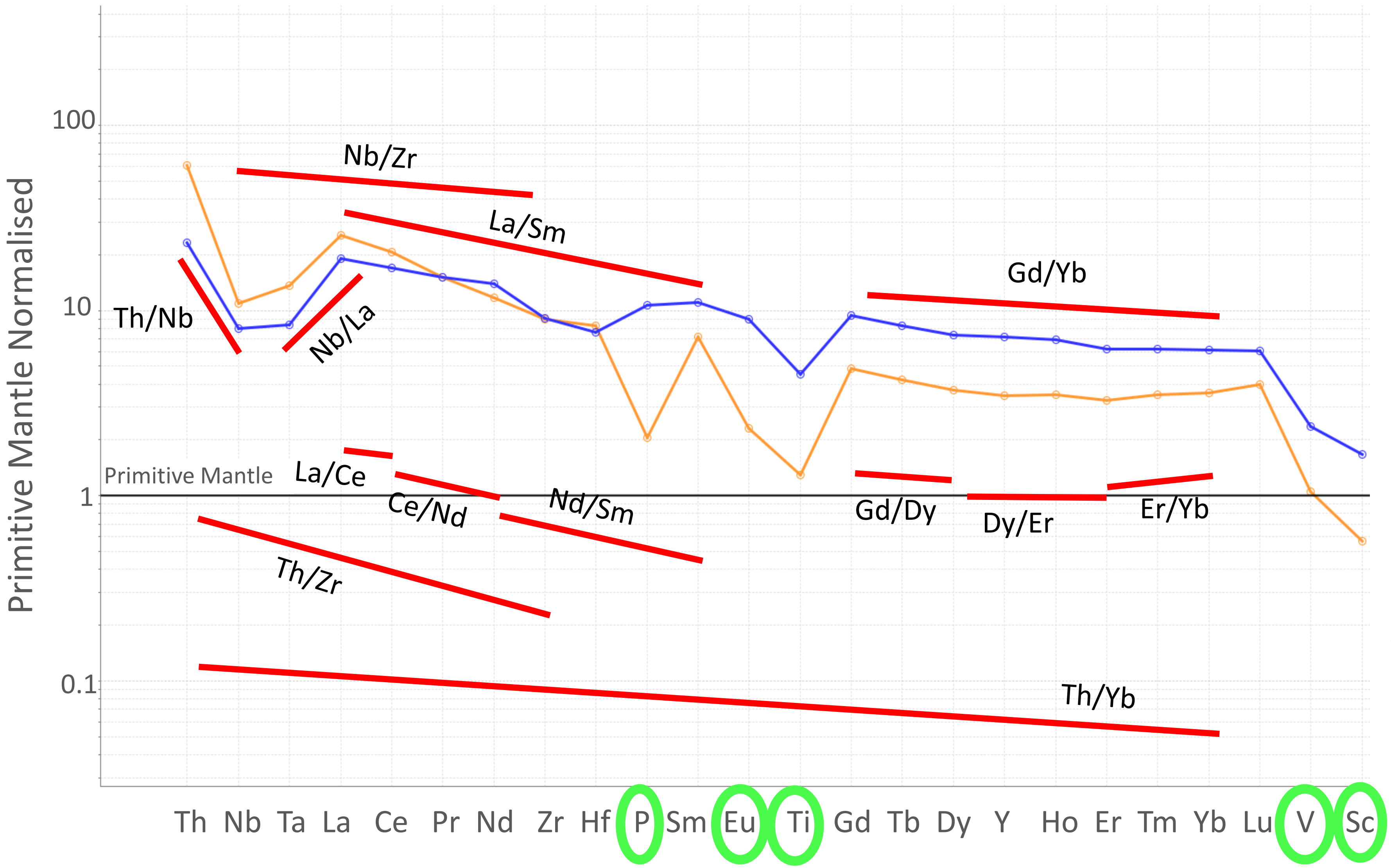




Incompatible element pairs maintain very similar ratios across a wide range of compositions

That makes them very useful for discriminating different <u>magma series</u>

Lithogeochem Calculator

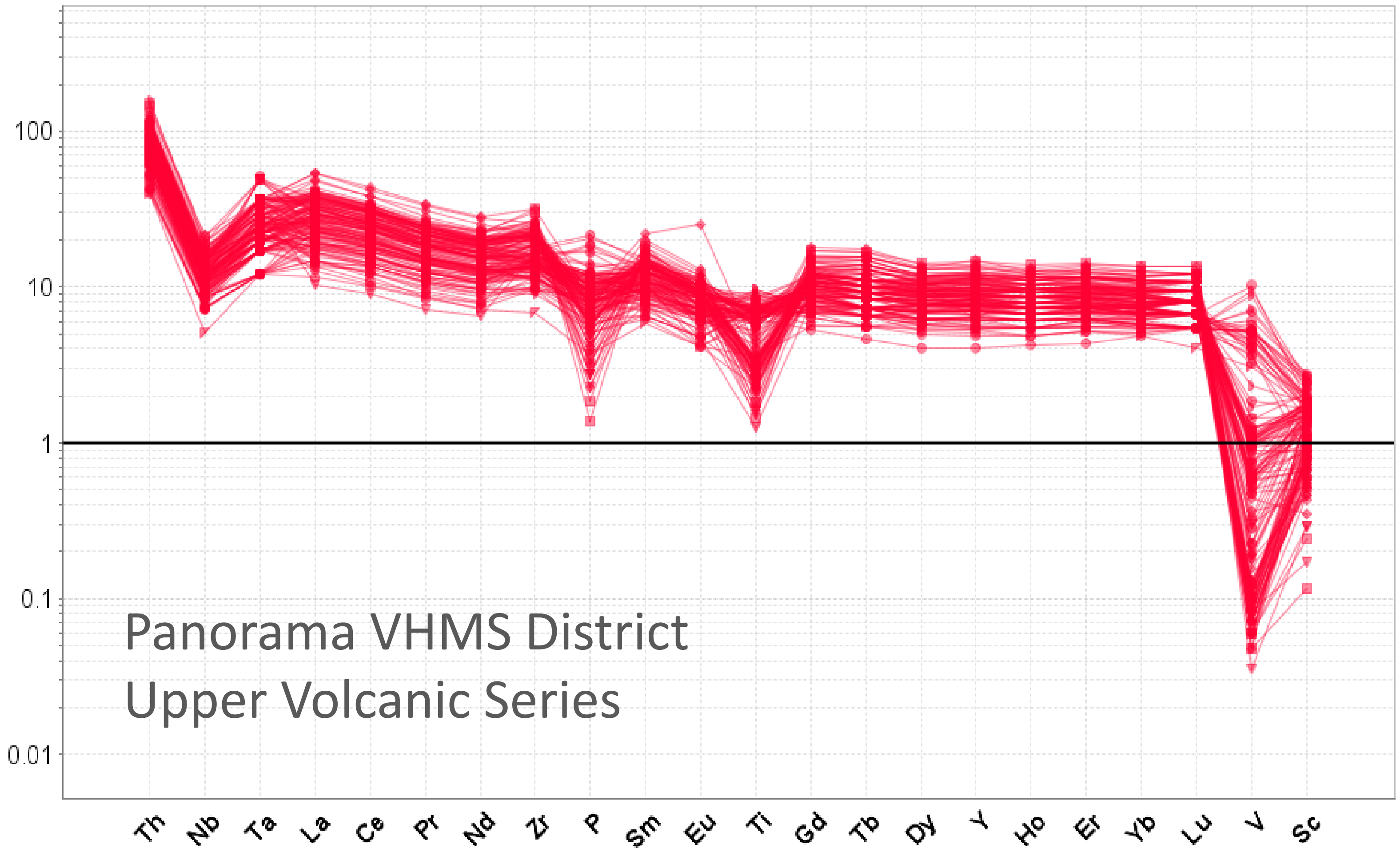


Lithogeochem Calculator compares 13 element ratios to quantify difference between profiles for two samples

Compatible elements: ◯ are avoided because they vary according to fractionation

Discriminating Magma Series

Use incompatible element ratios to discriminate between magma series
Use compatible elements to discriminate within a magma series

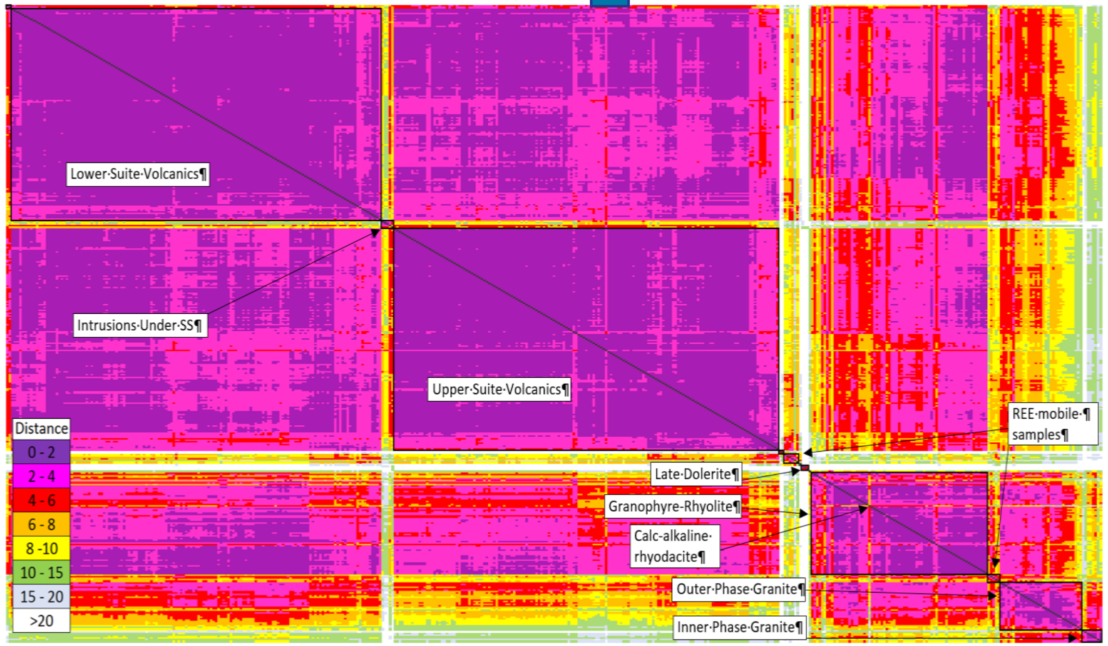


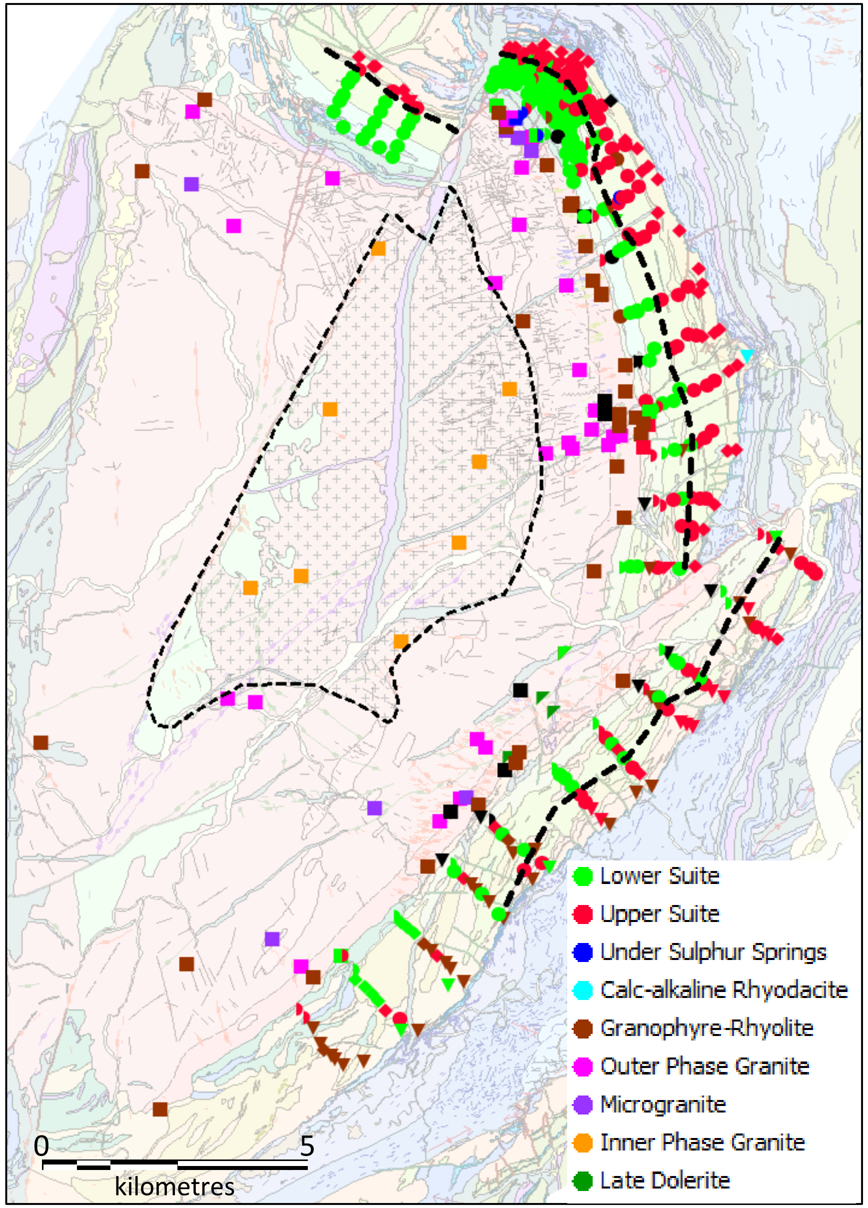
Lithogeochem Calculator

Panorama VHMS District

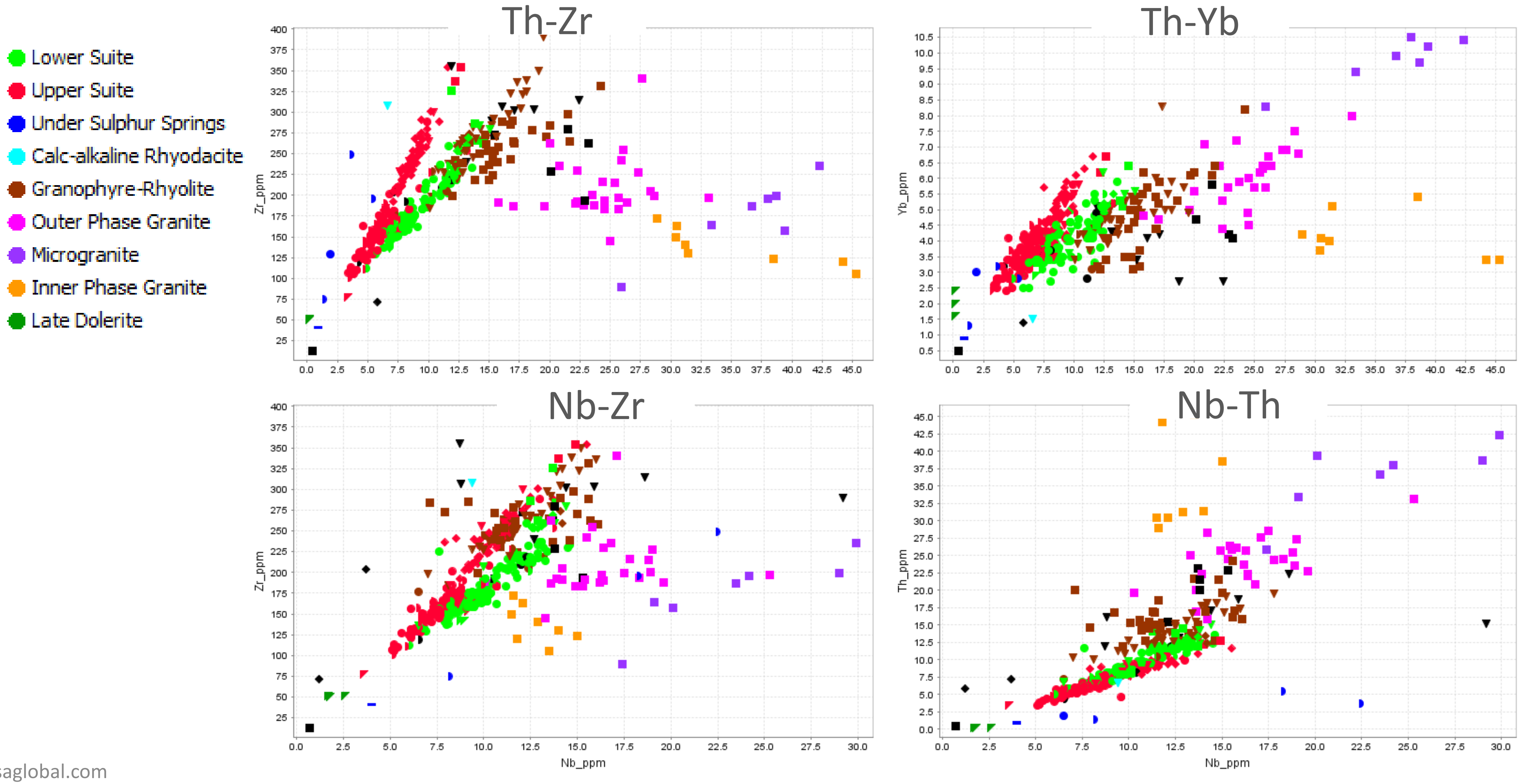
440 rock chip samples classified using Lithogeochem Calculator

Spatially coherent domains result

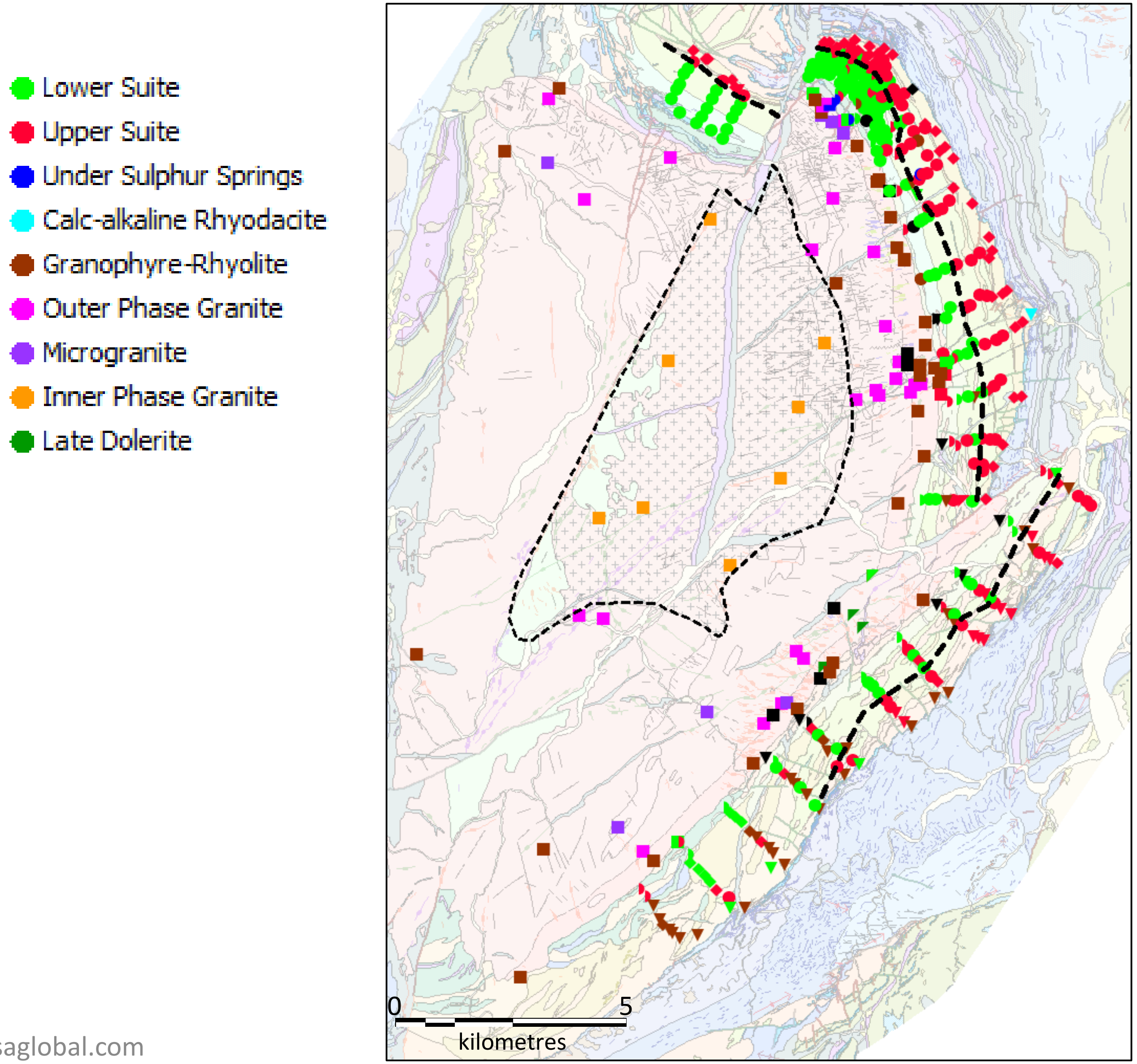


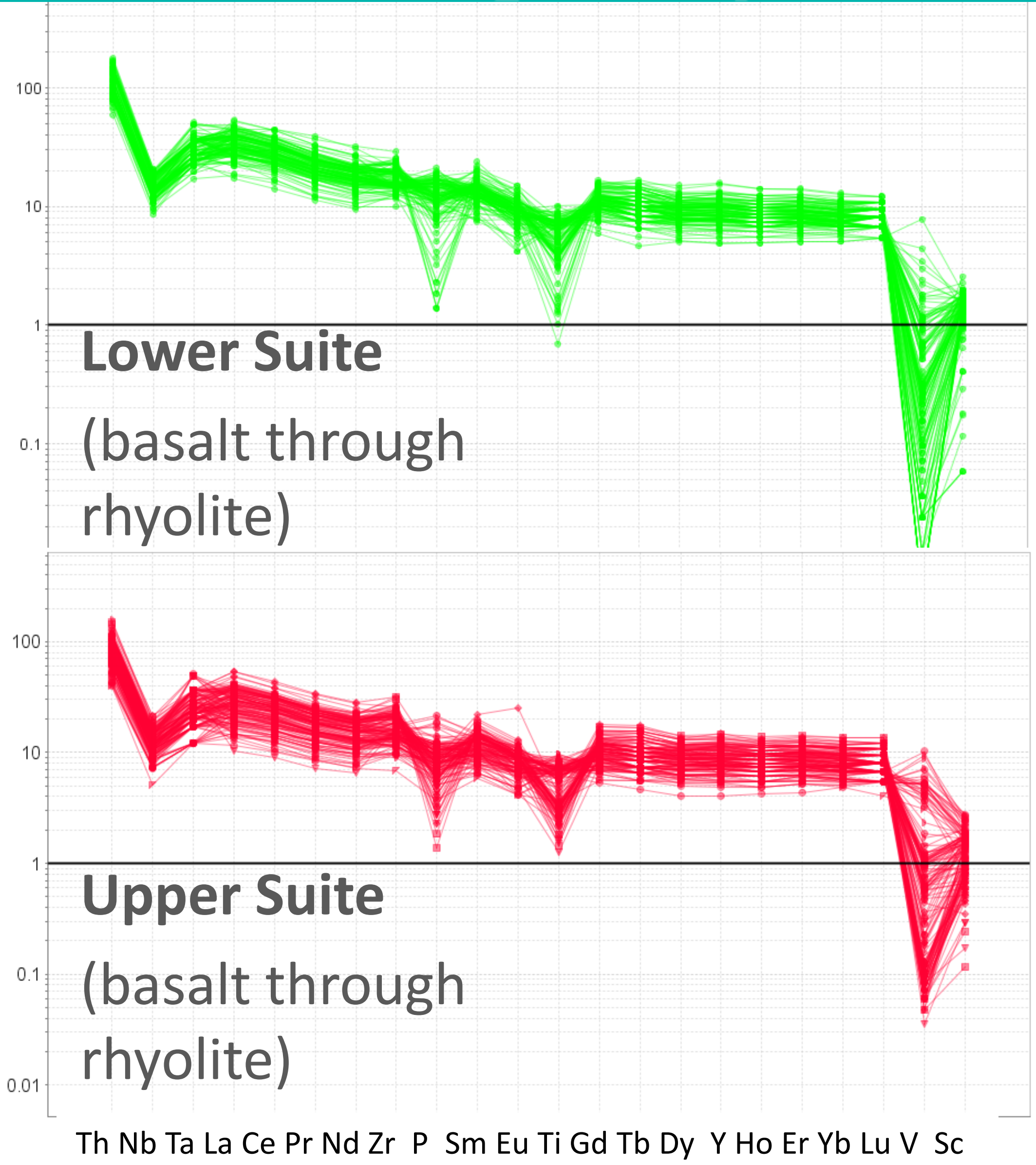


Panorama VHMS: Rapidly Classify Bi-plots



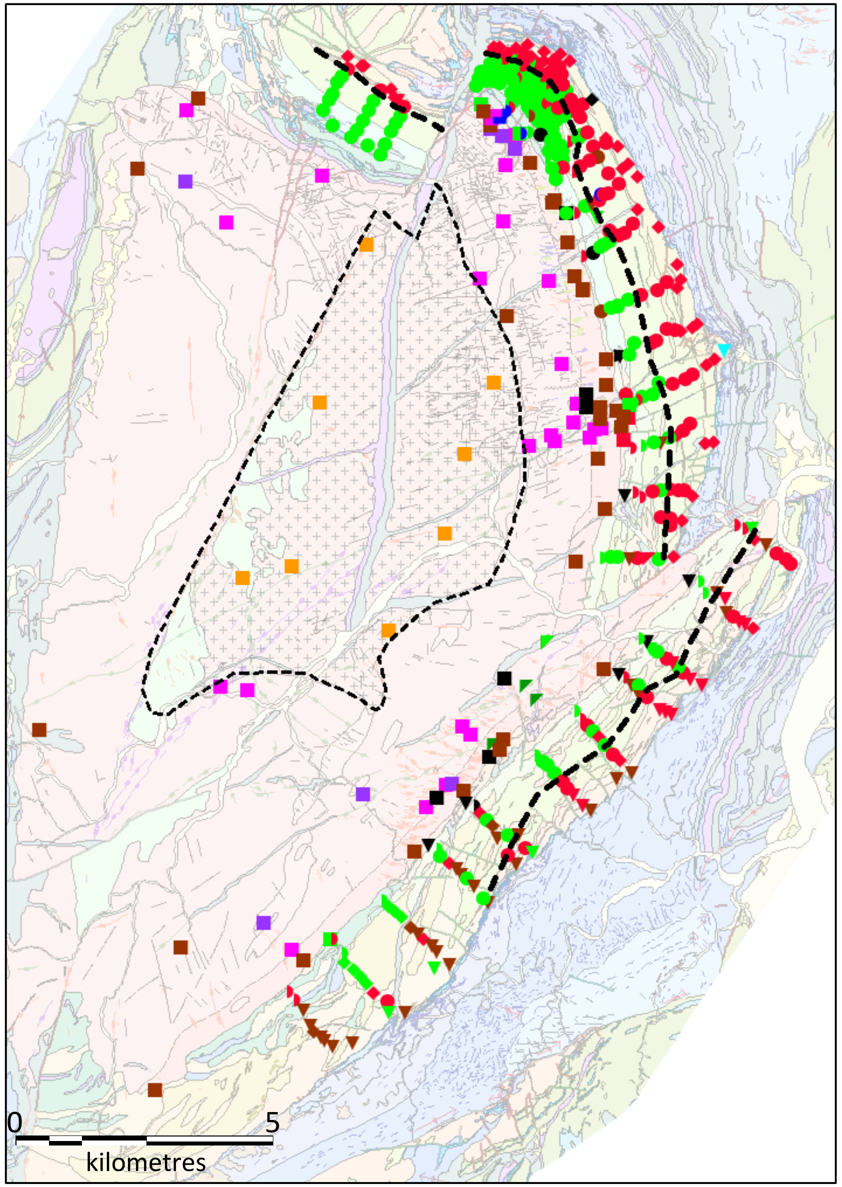
Panorama VHMS: Upper and Lower Volcanic Suites

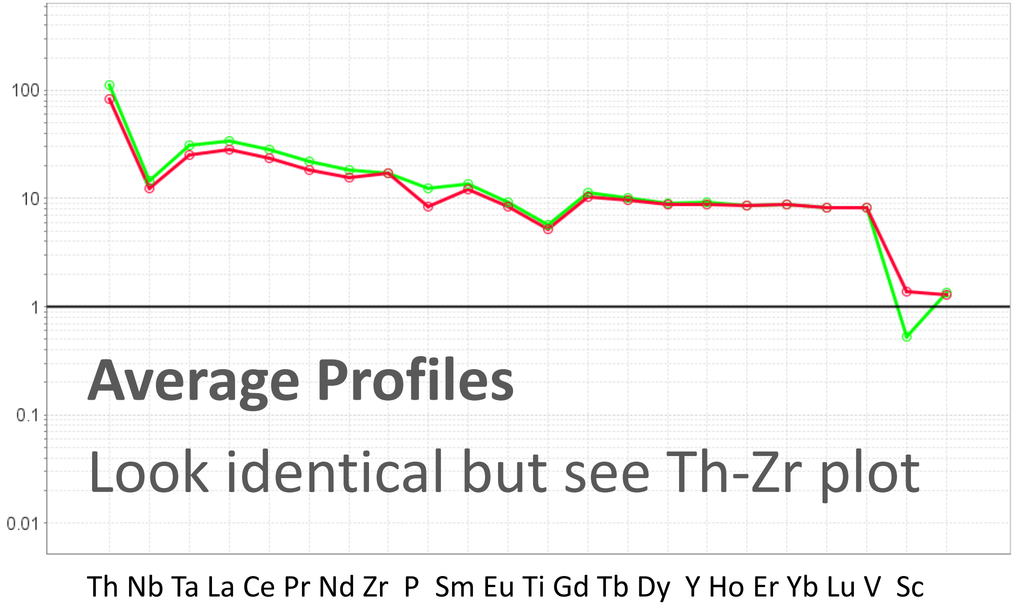


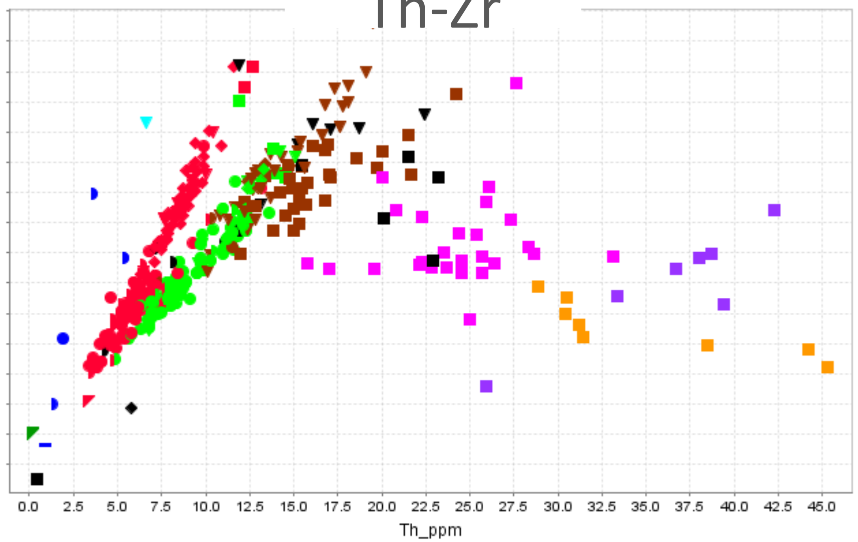


Panorama VHMS: Upper and Lower Volcanic Suites

- Lower Suite
- Upper Suite
- Under Sulphur Springs
- Calc-alkaline Rhyodacite
- Granophyre-Rhyolite
- Outer Phase Granite
- Microgranite
- Inner Phase Granite
- Late Dolerite





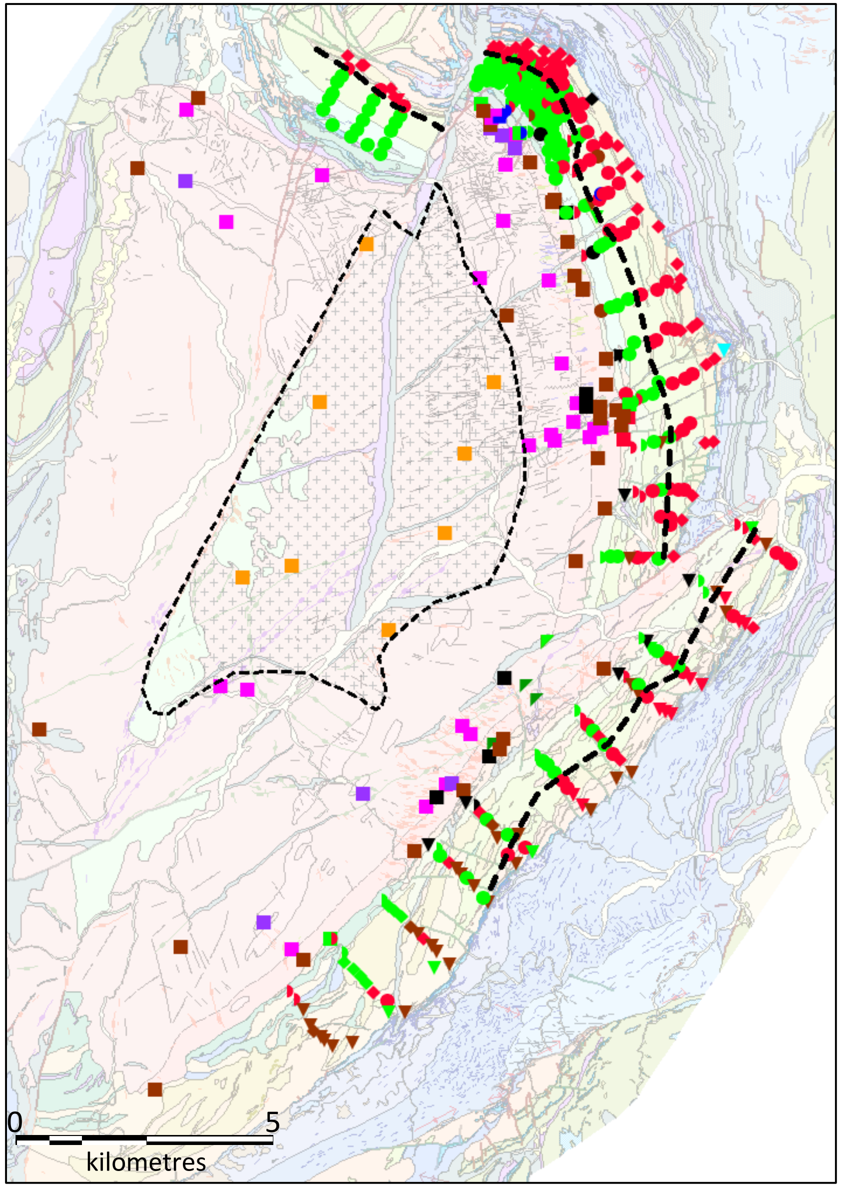


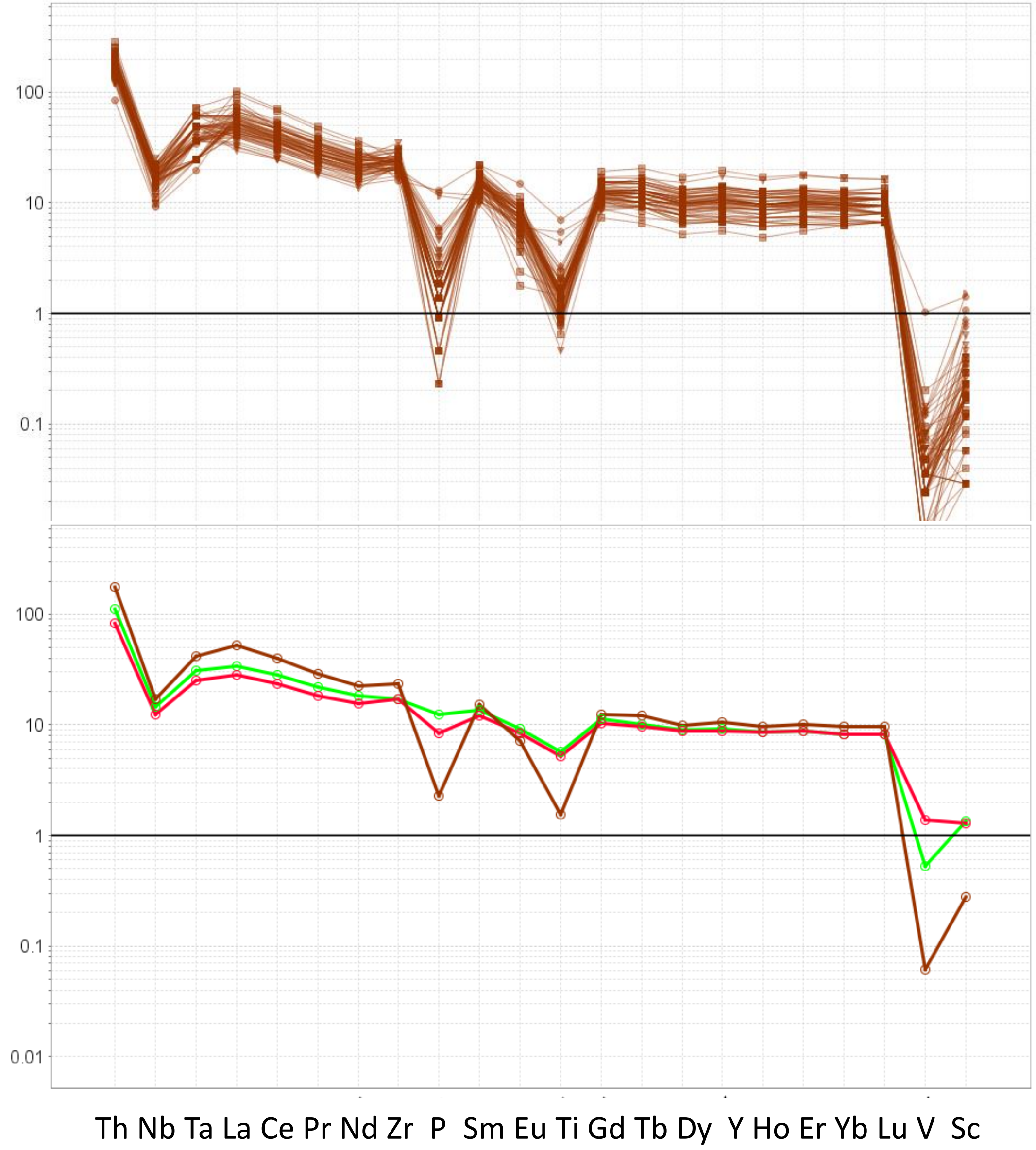
Previously Unrecognised Suite

Volcanic and granite

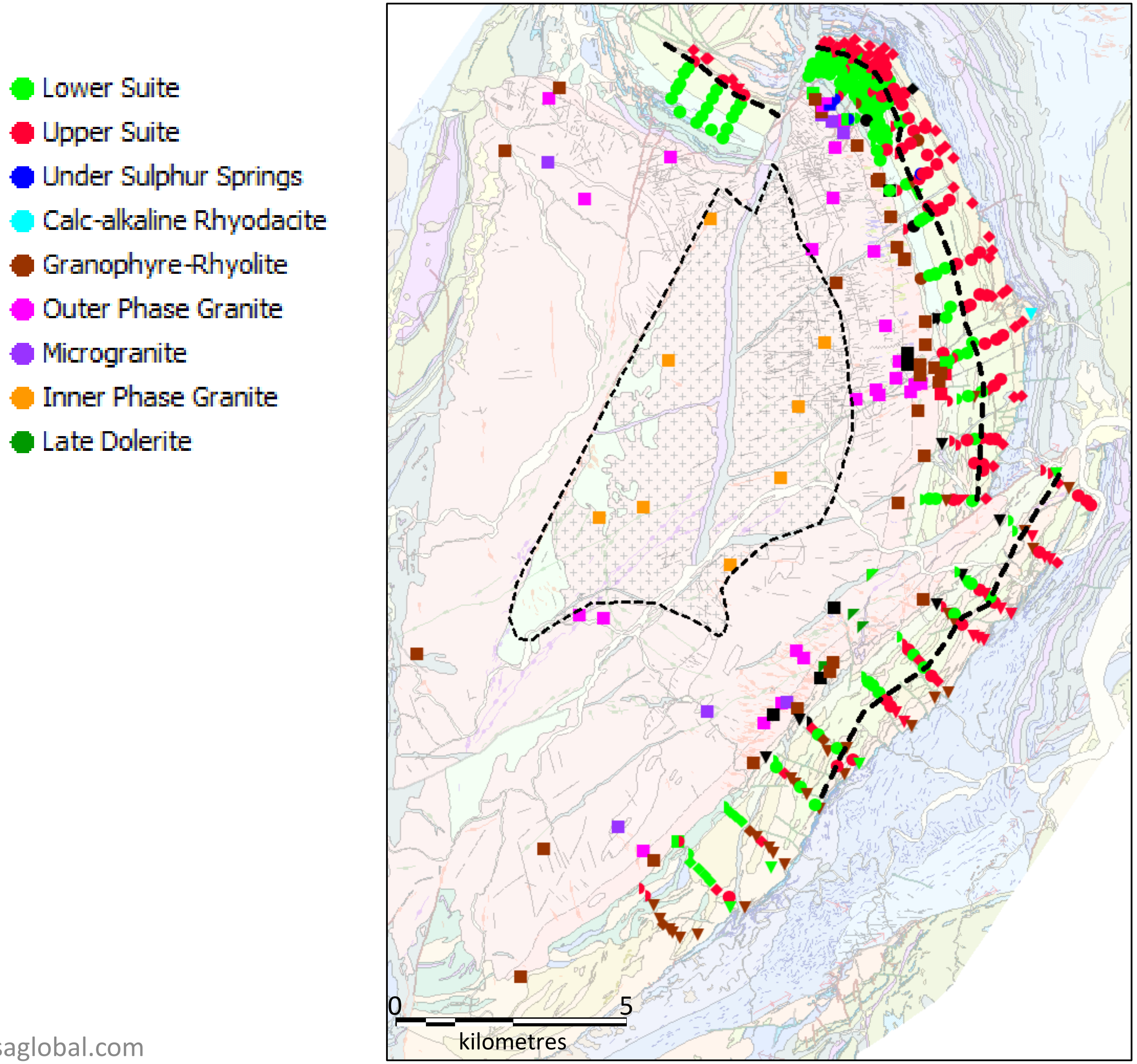
Third suite has subtly higher

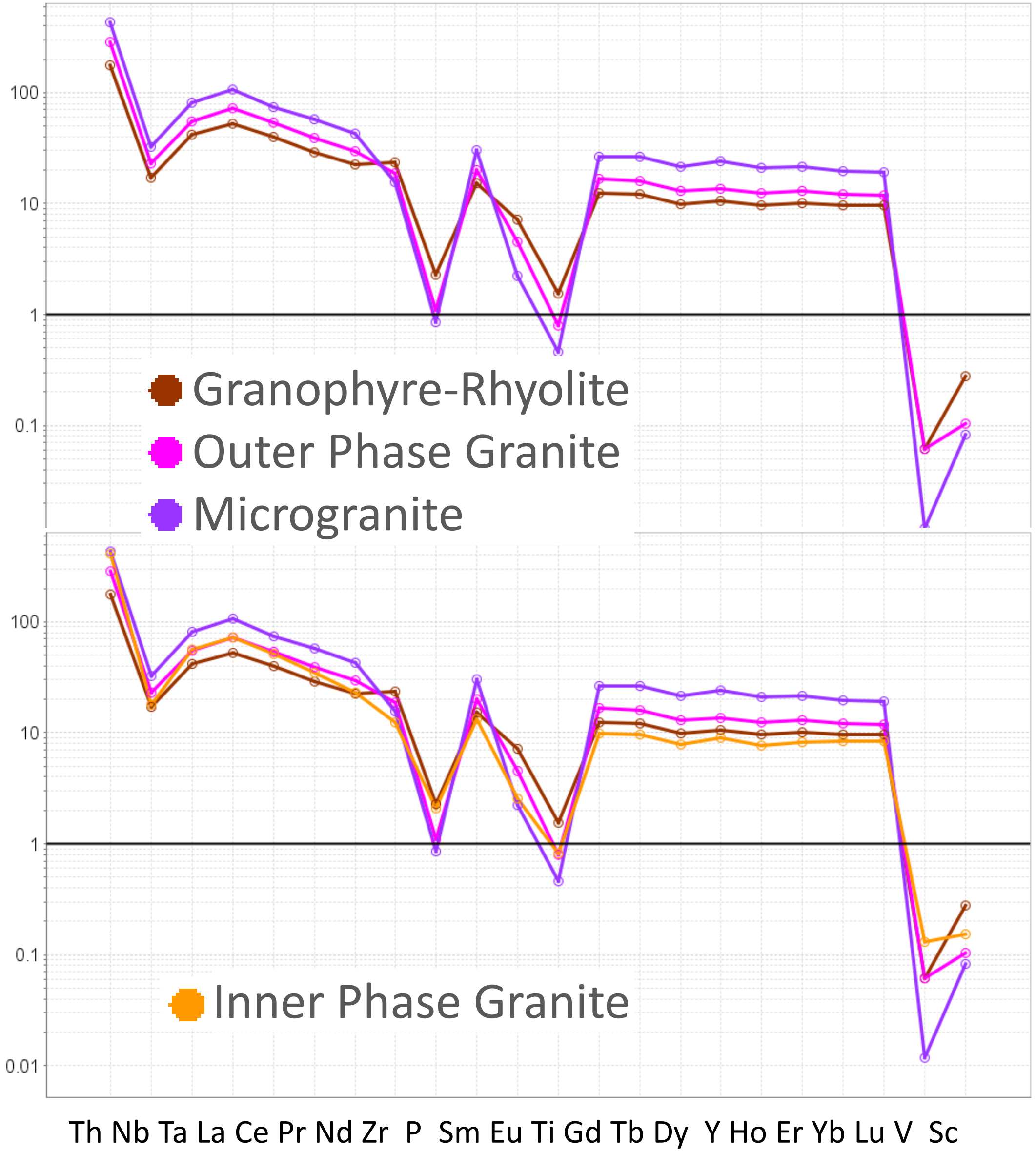
Th/Yb & La/Yb



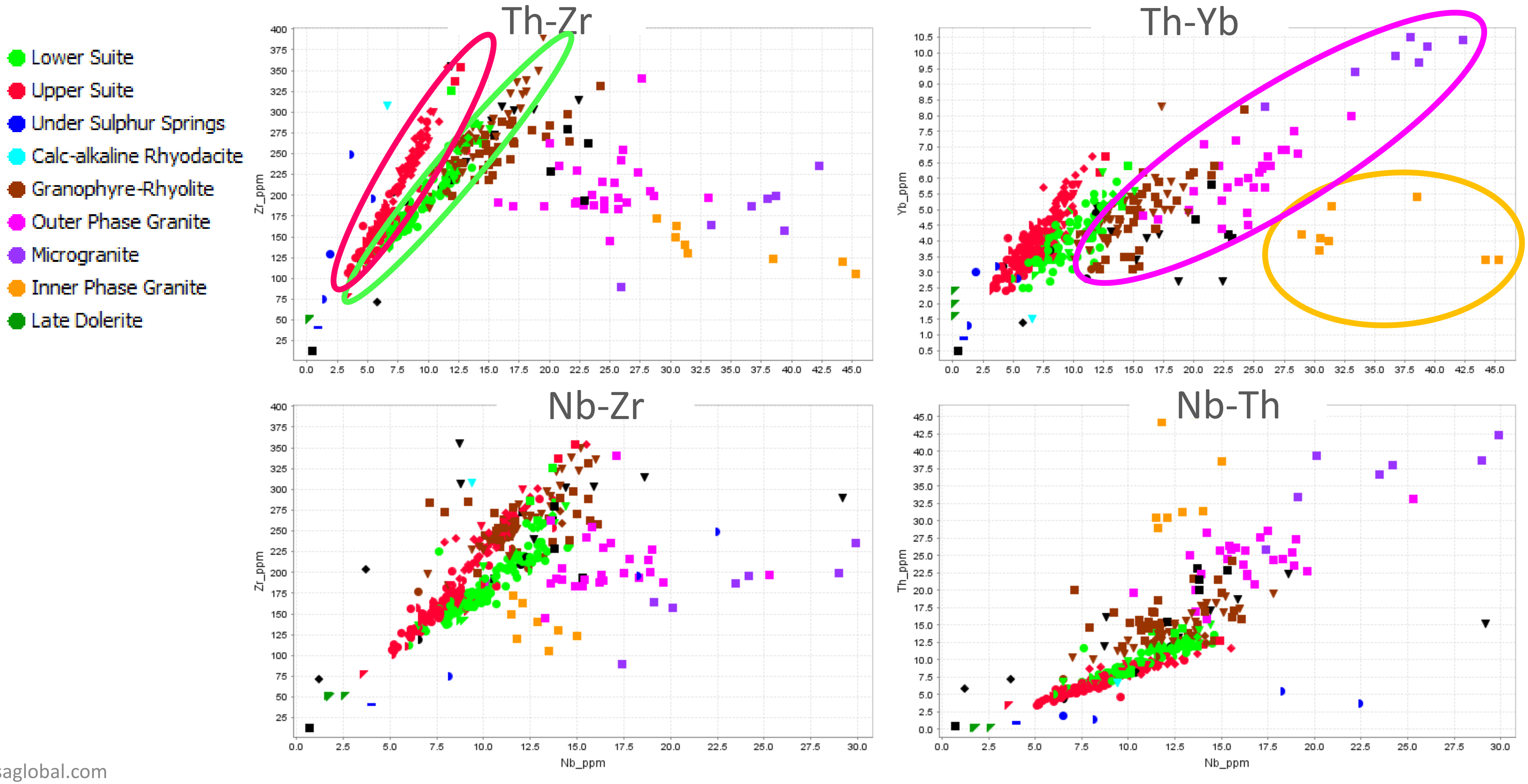


Panorama VHMS: Outer and Inner Phase Granite

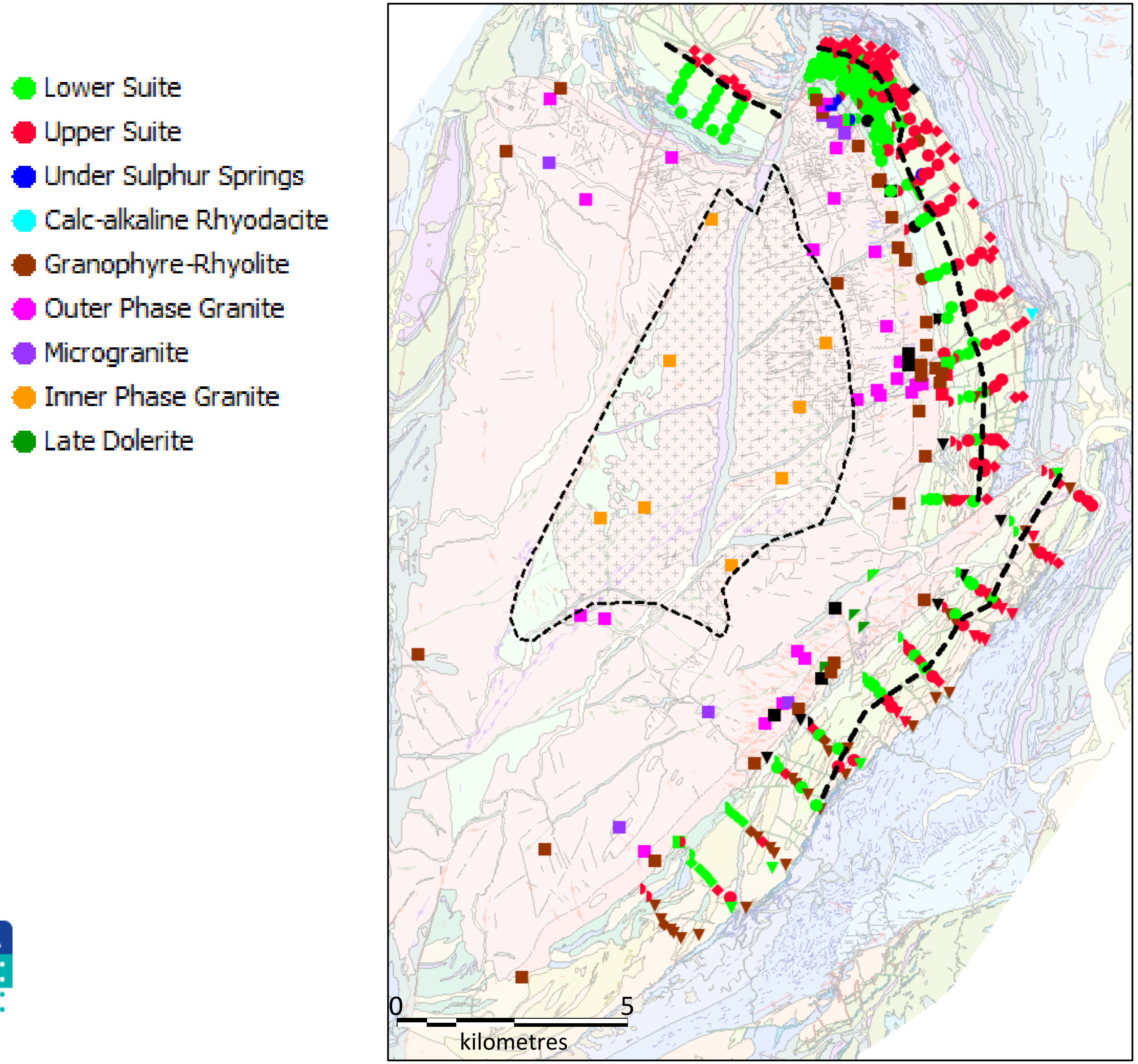




Panorama VHMS: Rapidly Classify Bi-plots



How Has This Helped?



- Ti-Zr has been used to validate mapping of compositions basalt through to rhyolite
- Detailed immobile element geochemistry defines a break in volcanic stratigraphy – VHMS implications
- Four major magma series helps unravel the order of events in the mineral system

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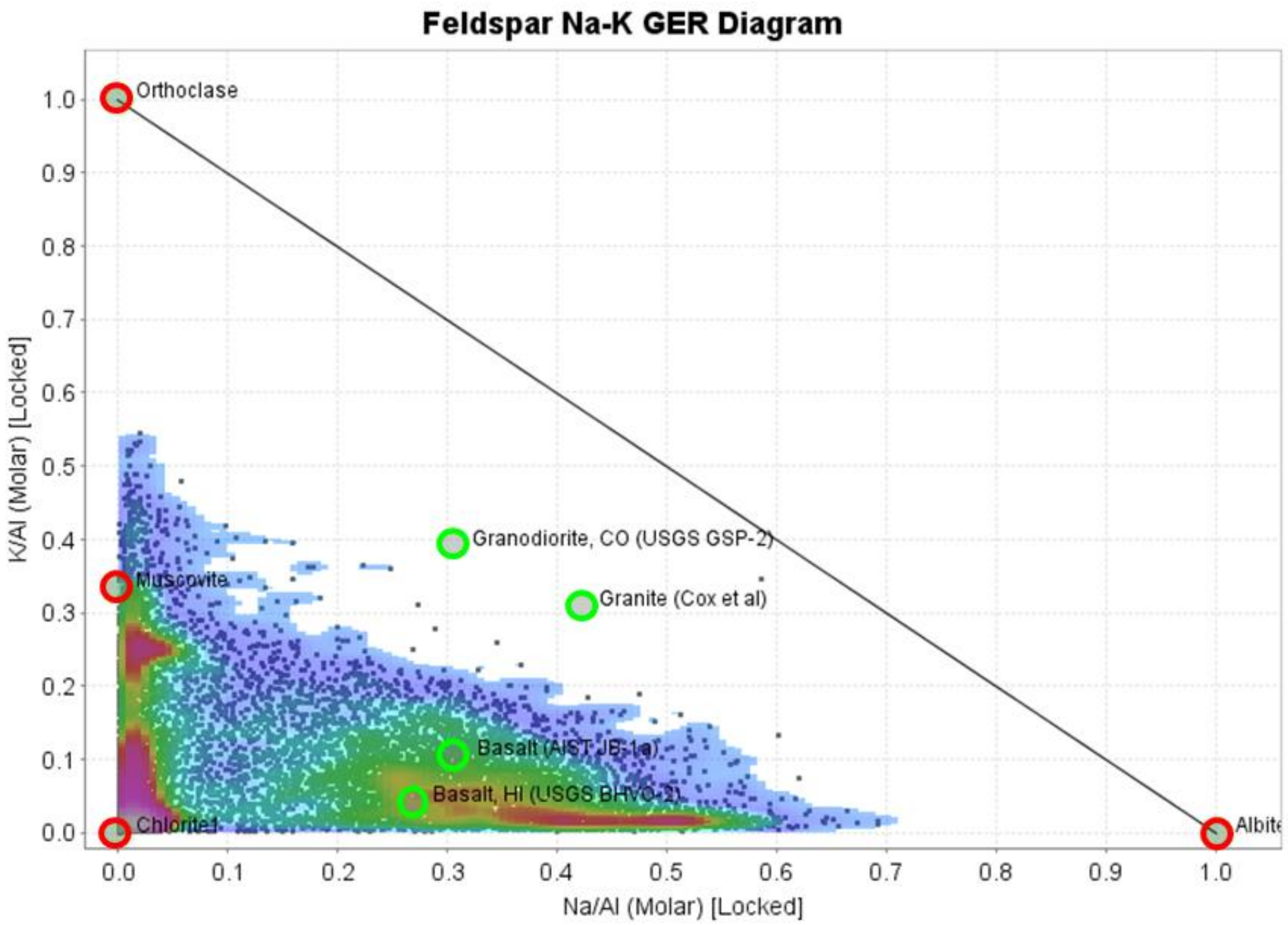
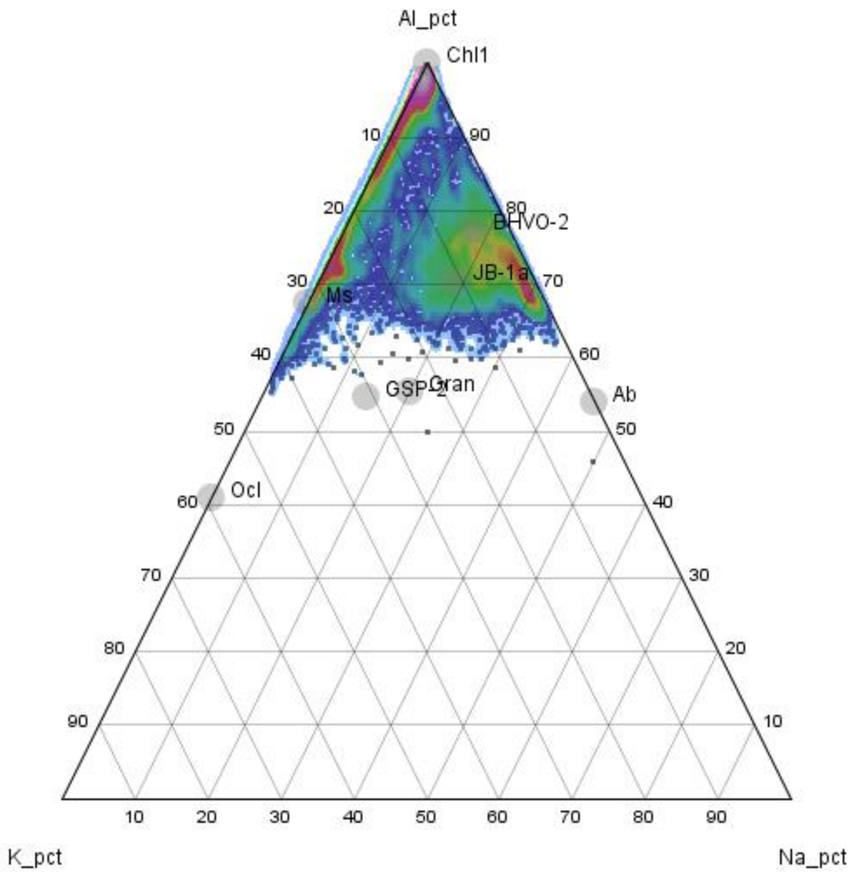
2. Alteration Geochemistry

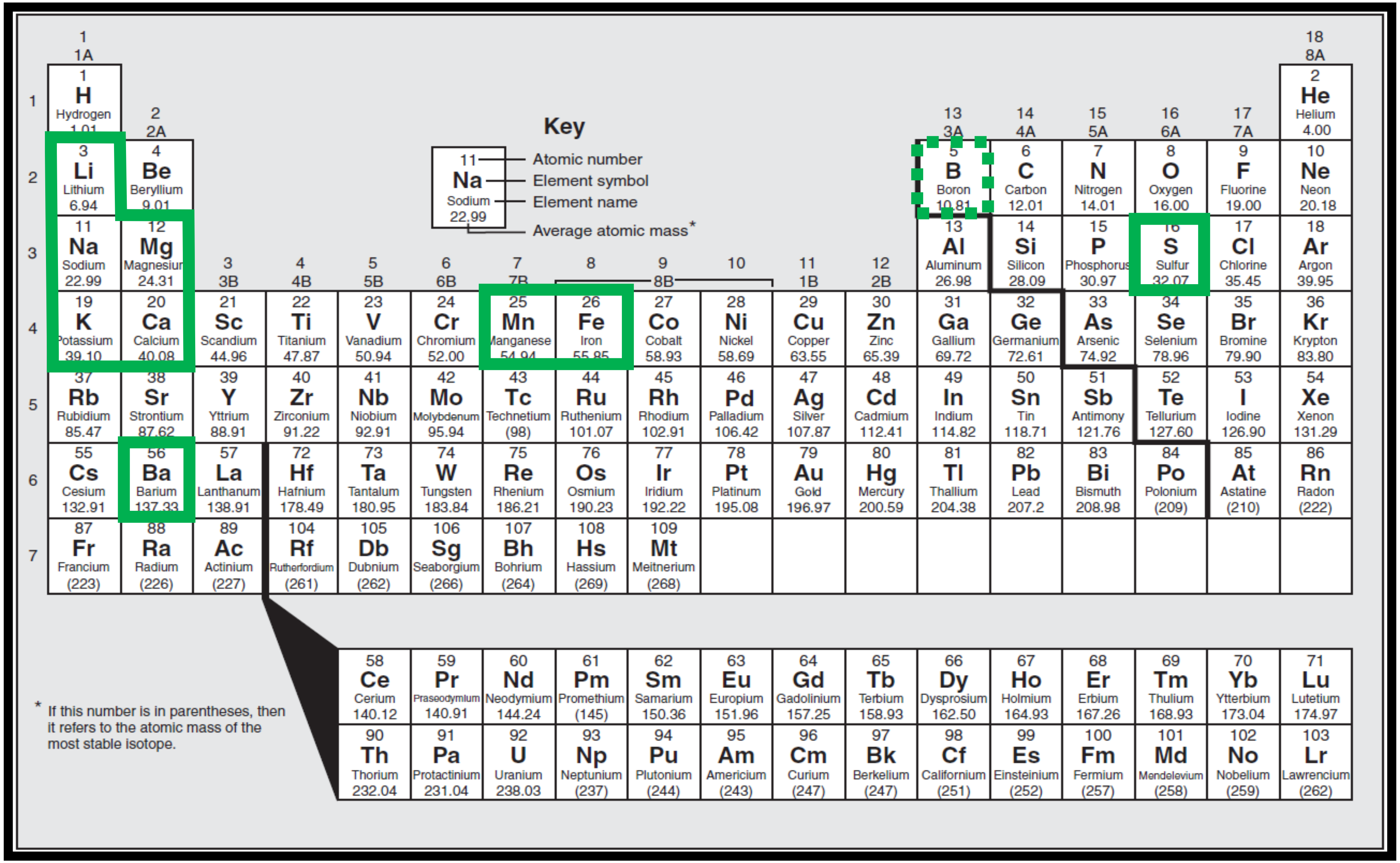
Alteration Diagrams

On any diagram, ask “What minerals are likely to be driving trends on my diagram?”. It’s all about minerals

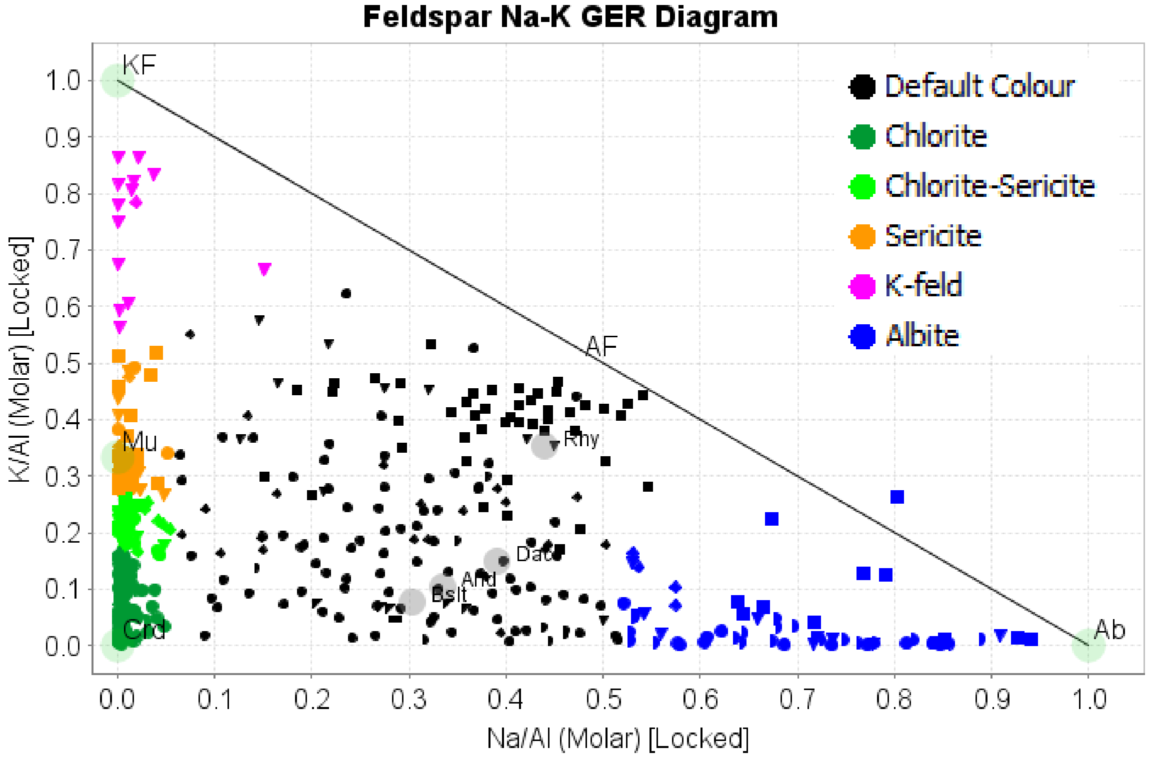


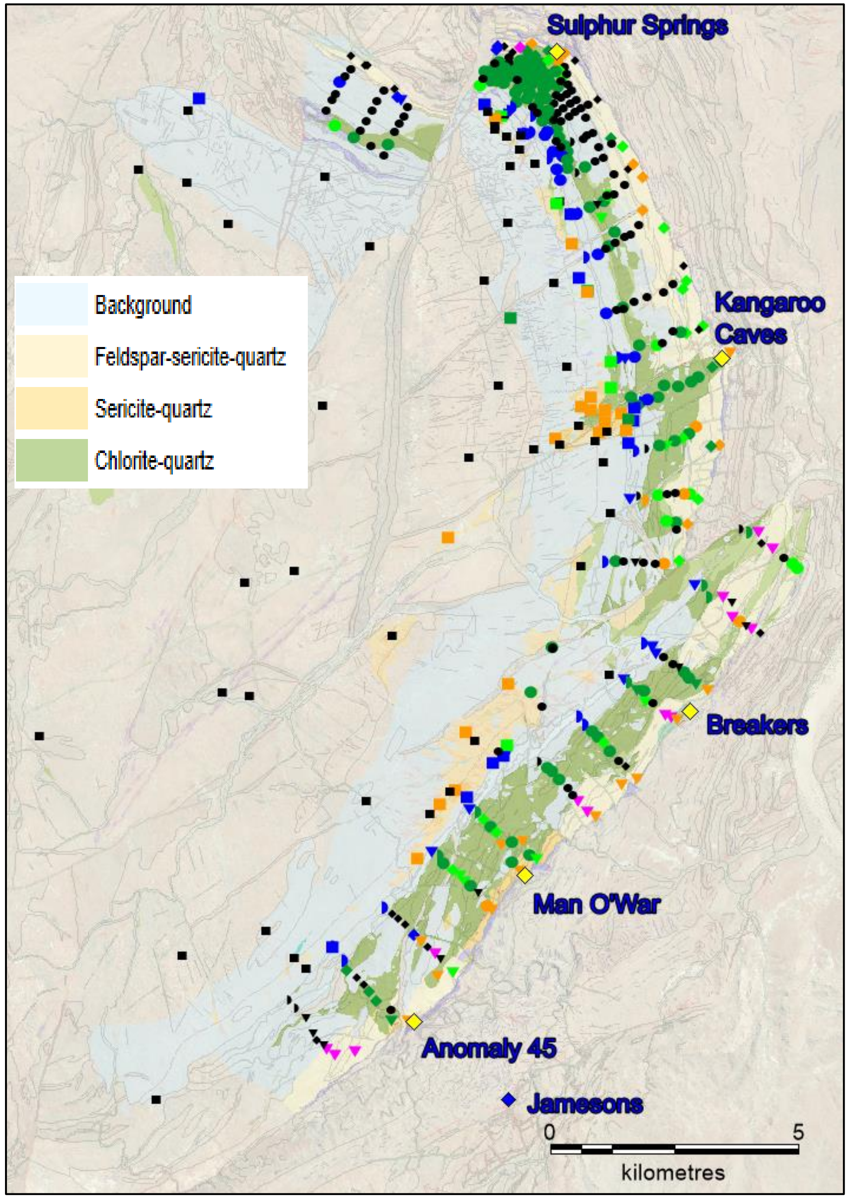


Alteration Elements

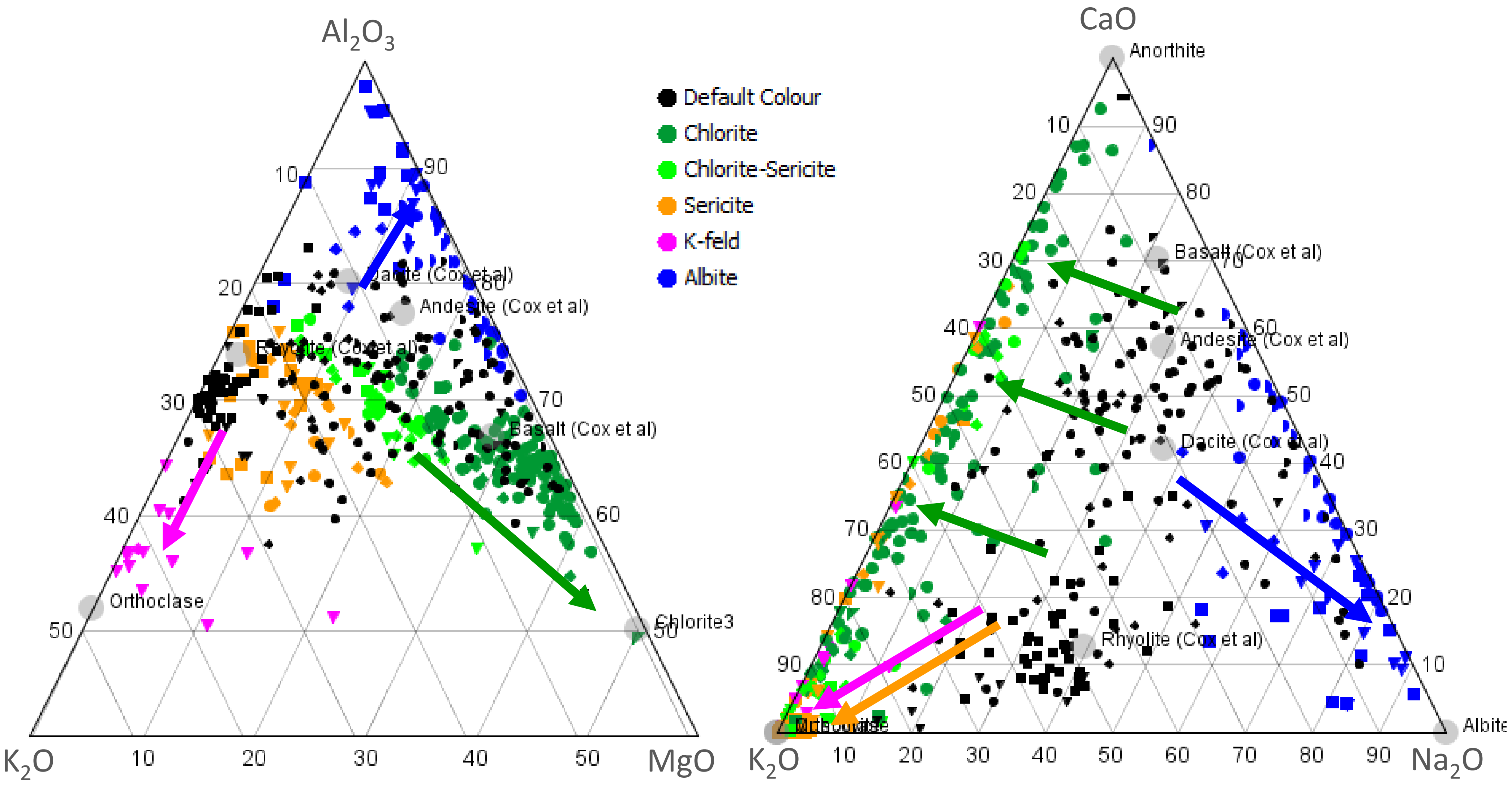


Panorama VHMS Mineral System

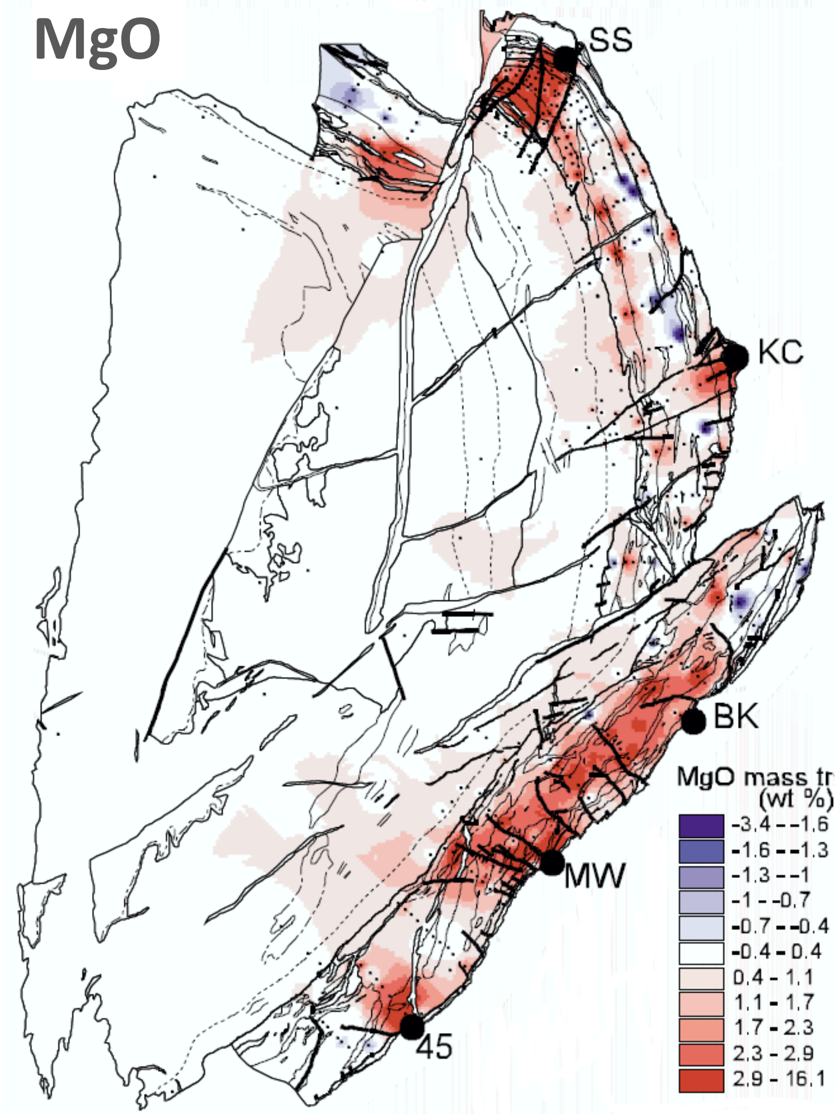


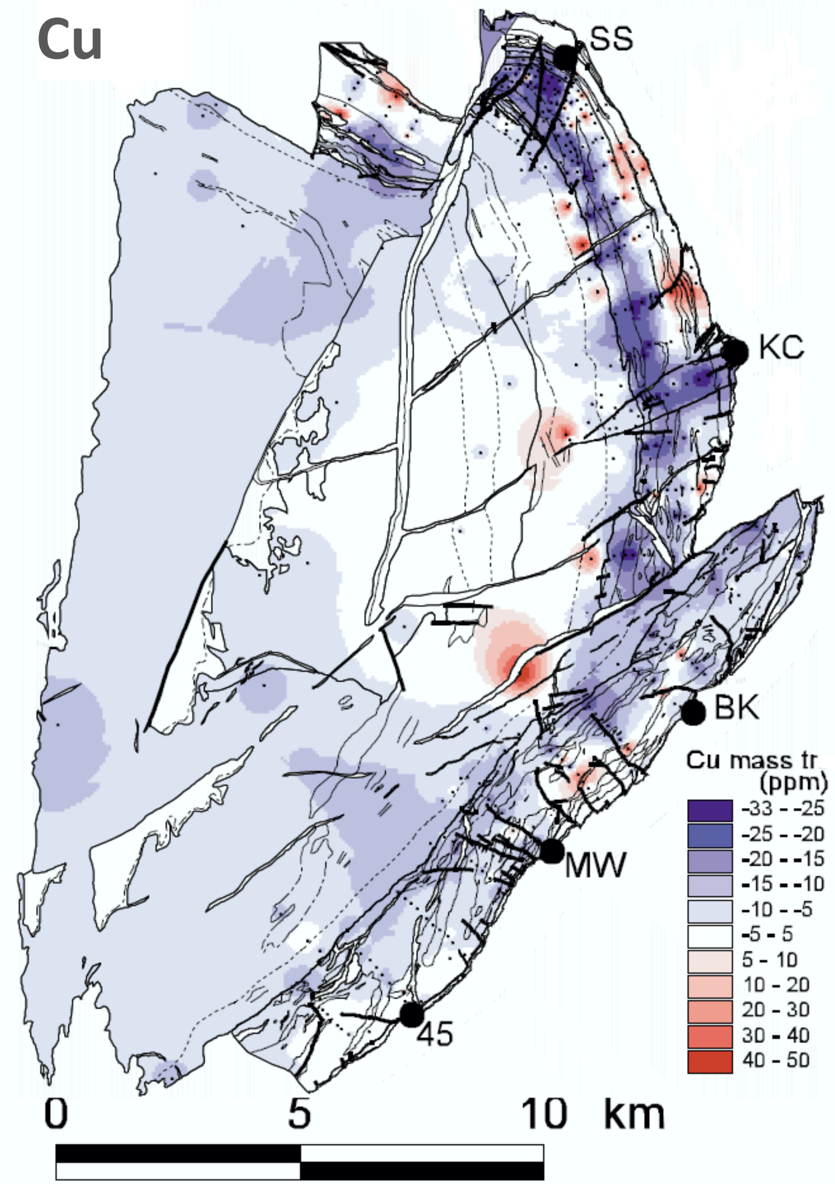


Panorama VHMS Mineral System



Panorama VHMS Mineral System: Mass Transfer Maps





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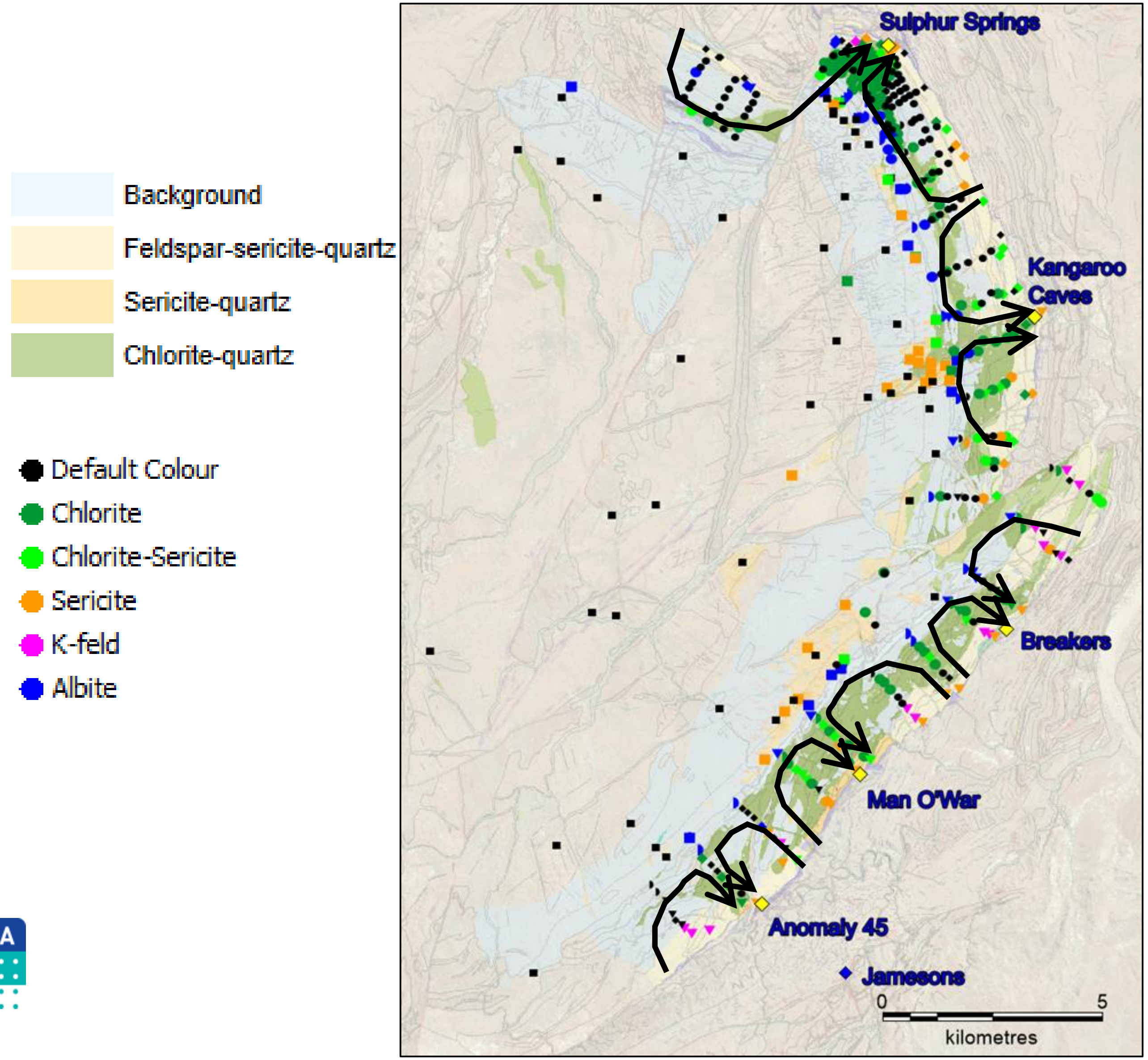
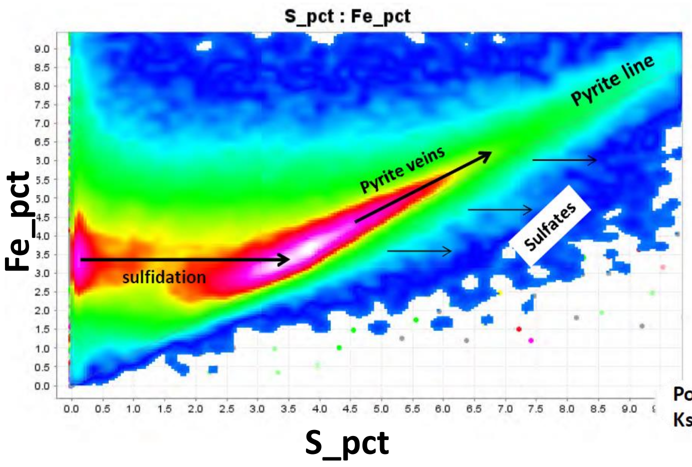
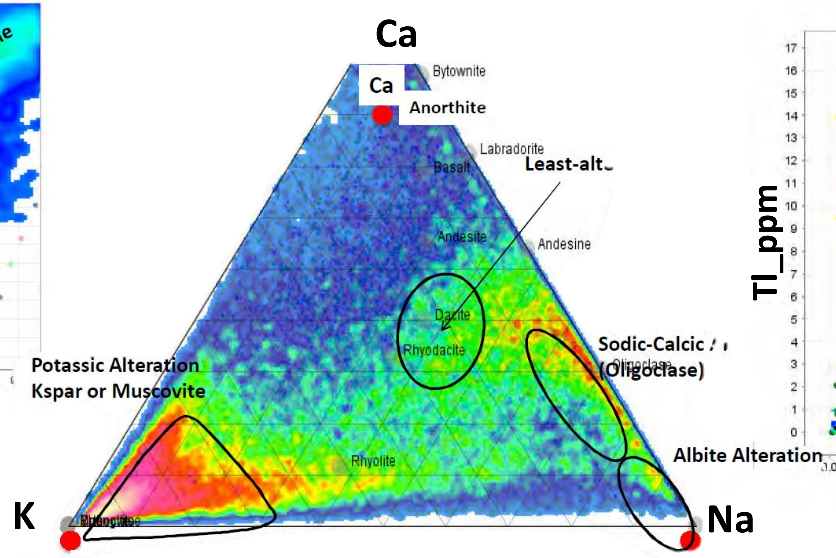
How Has This Helped?

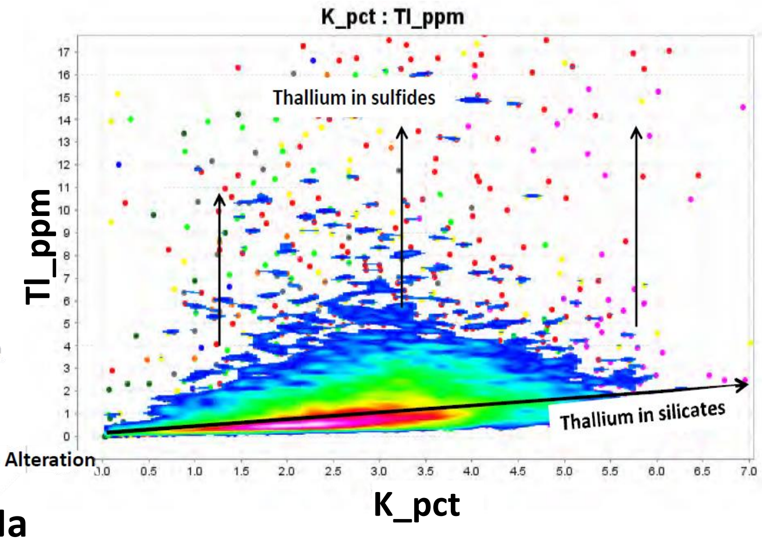


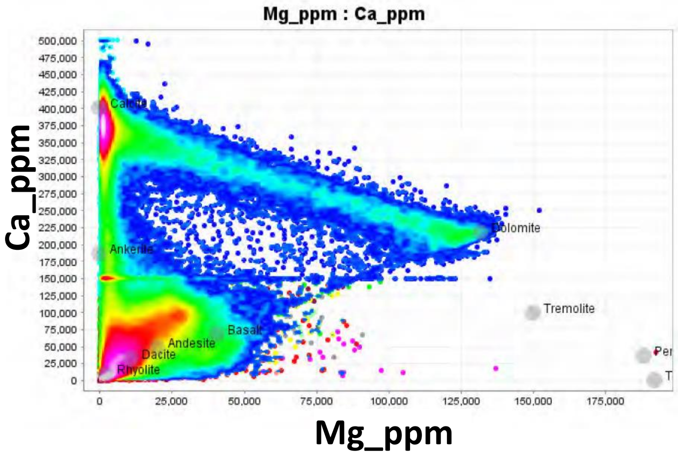
- Na/Al versus K/Al molar ratio plot confirms alteration mapping
- Architecture of alteration map can be interpreted as a convective hydrothermal system: discharge zones are targets
- Albite alteration coincides with zone of strong metal leaching = high temperature reaction zone

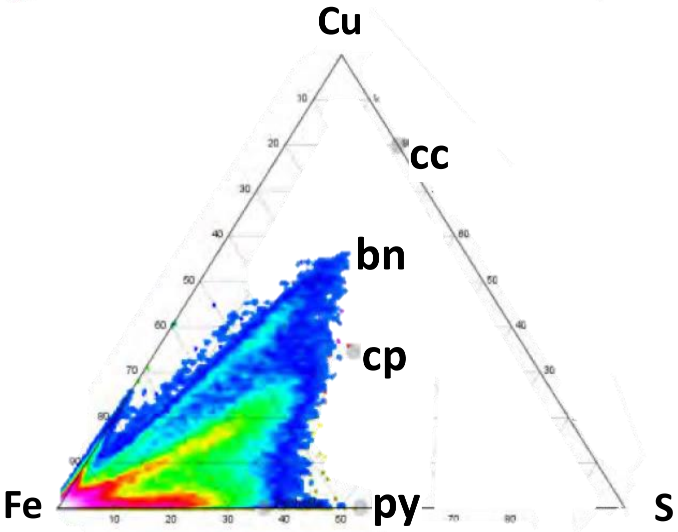
Choose Diagrams Appropriate to Your Mineral System

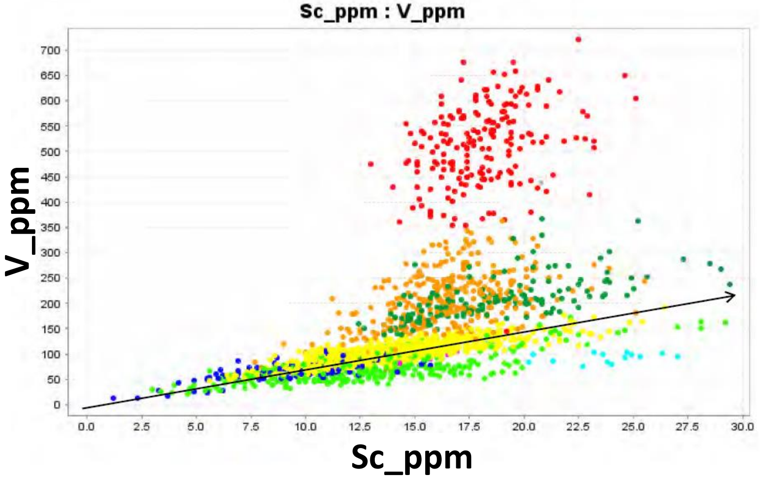












Halley (2016)

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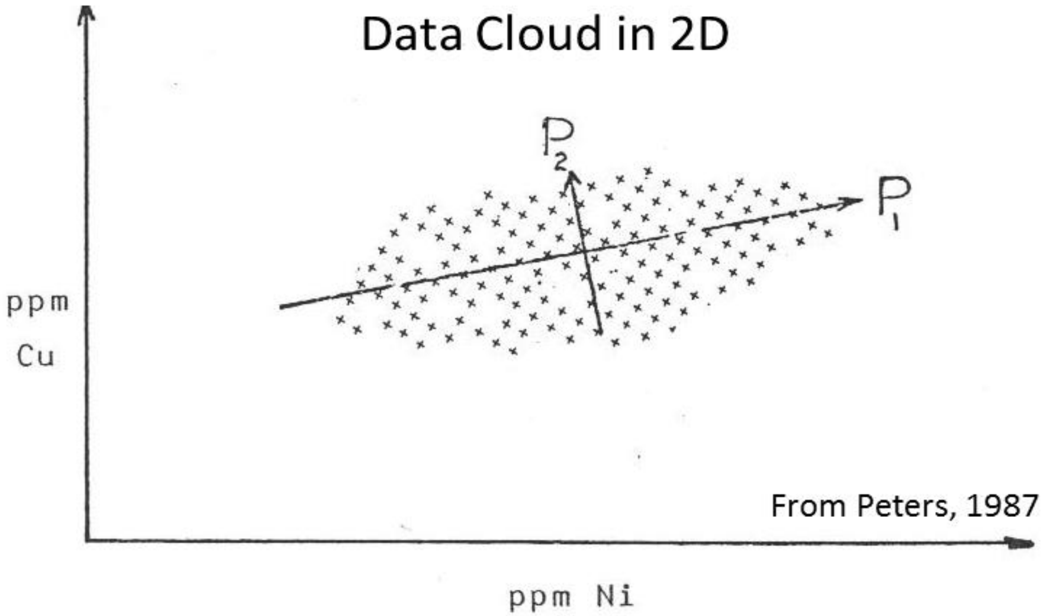
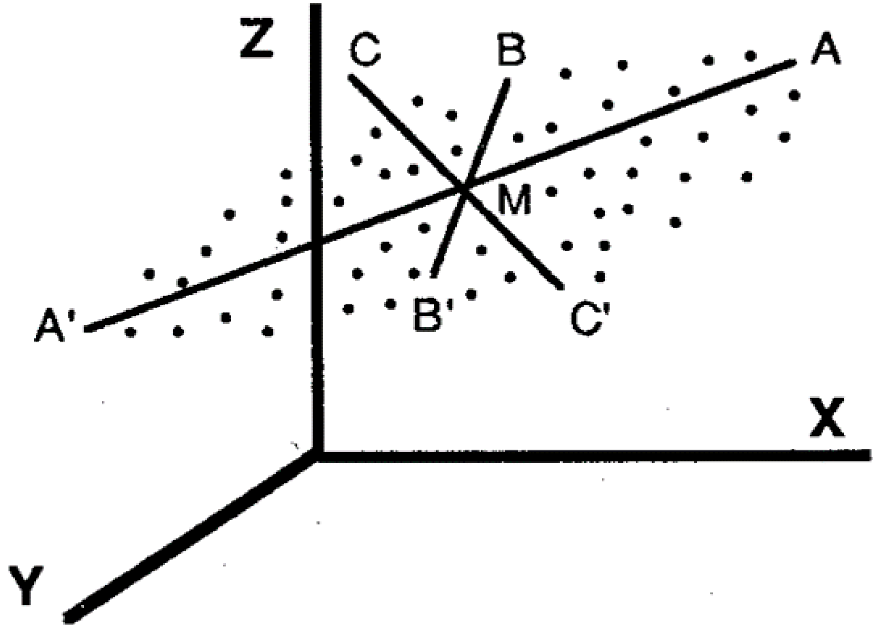
3. Mineralisation Signatures

Principal Component Analysis

- PCA is very useful to identify multielement associations: **Mineralisation**
- Rather than 40, or 60 individual elements, a handful of ranked scaled eigenvectors
- The proportion of variation owing to each element association (process) is defined

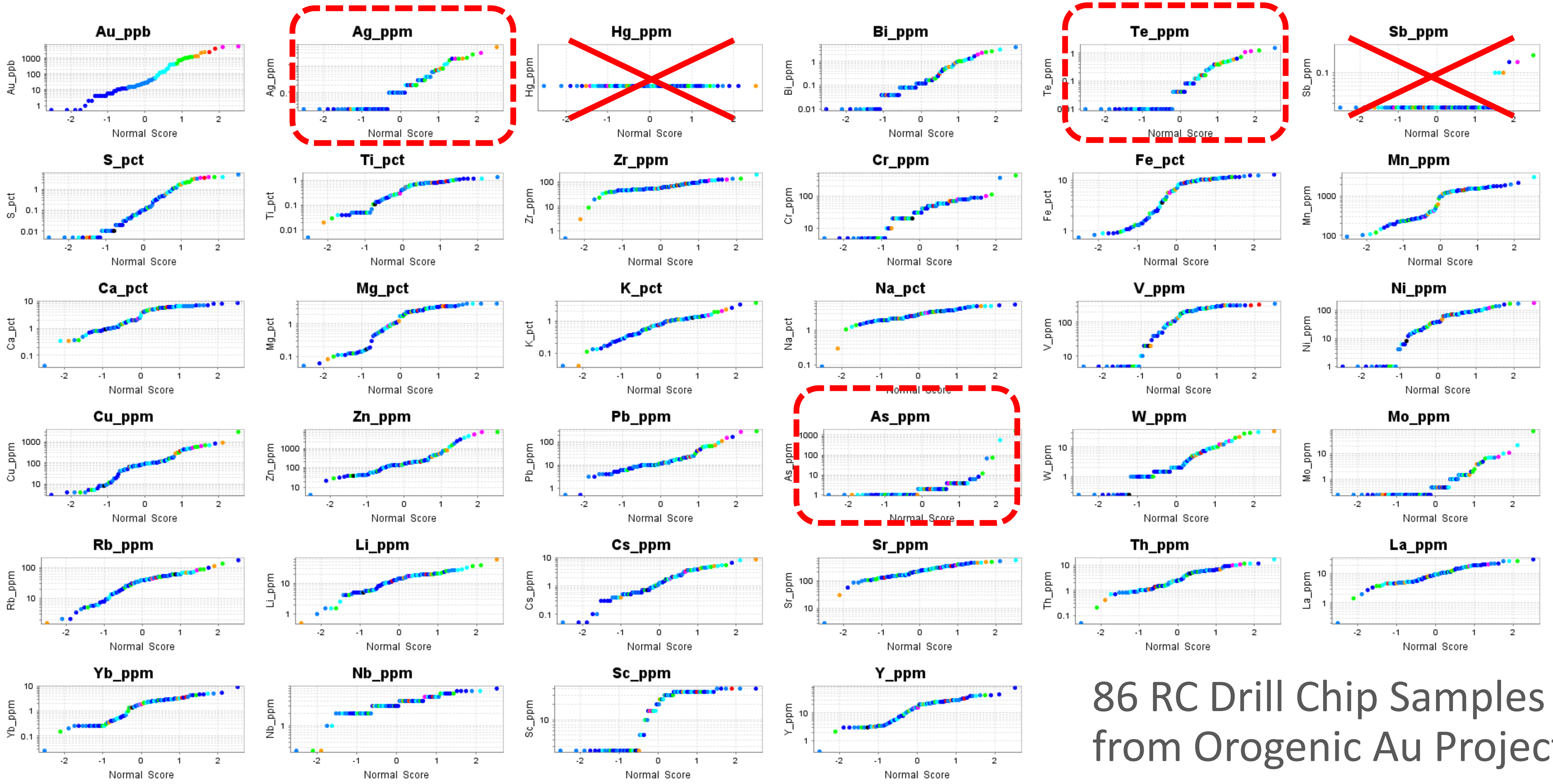
Single element maps mix all these processes together





Data Cloud in 3D

PCA Step 1: What to Include?

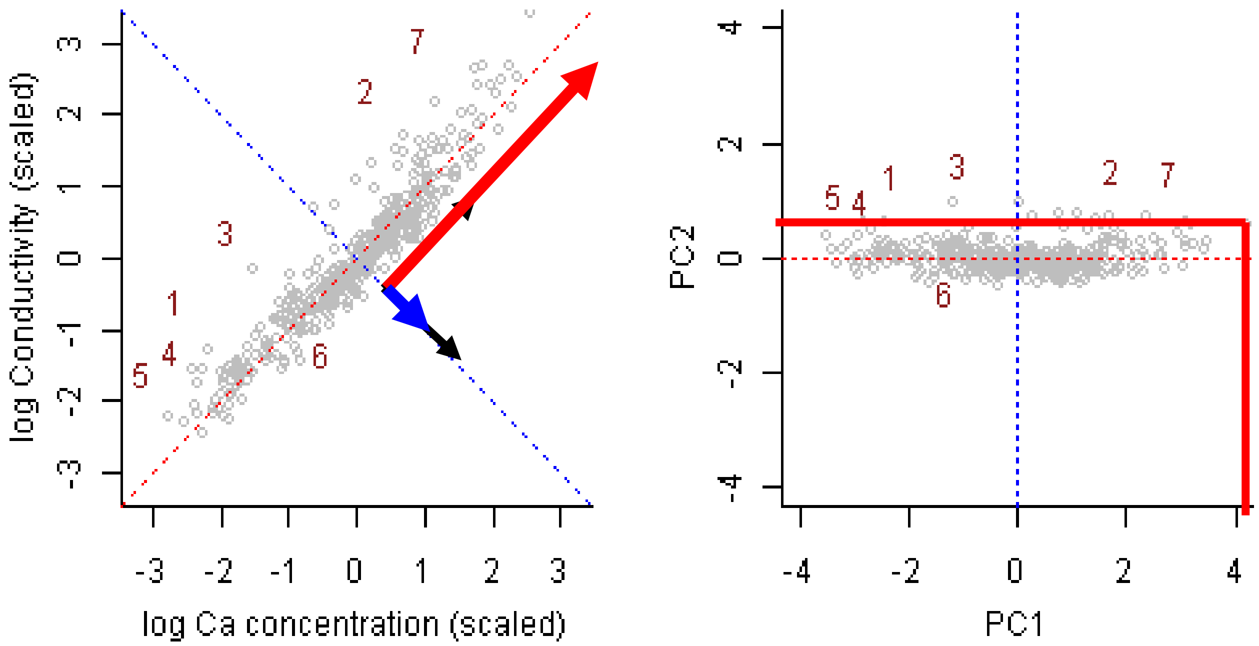


86 RC Drill Chip Samples from Orogenic Au Project

PCA Step 2: Centred Log Ratio Transform

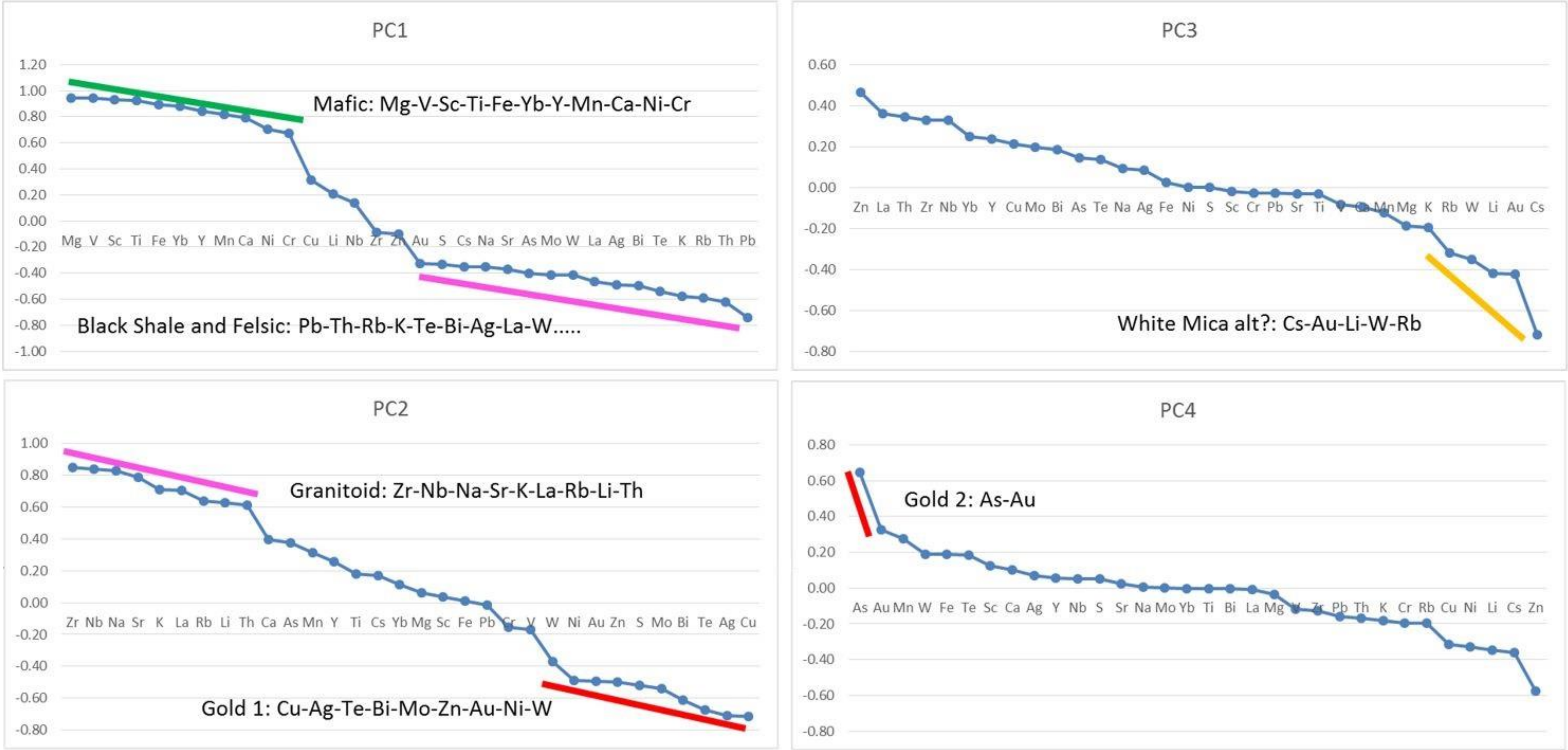
Let’s leave that for now

PCA Step 3: Calculate PCA

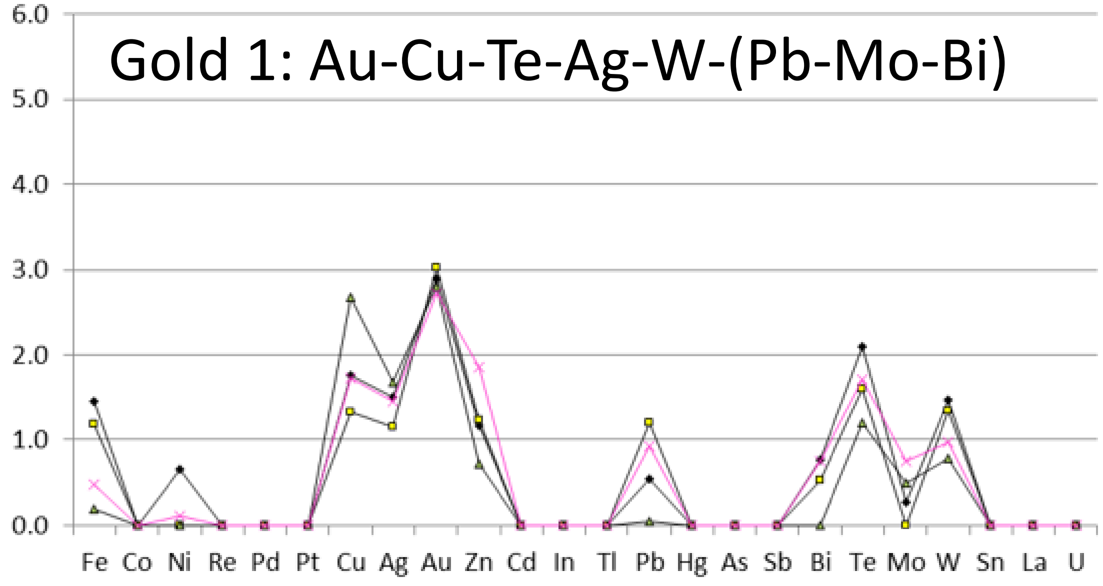


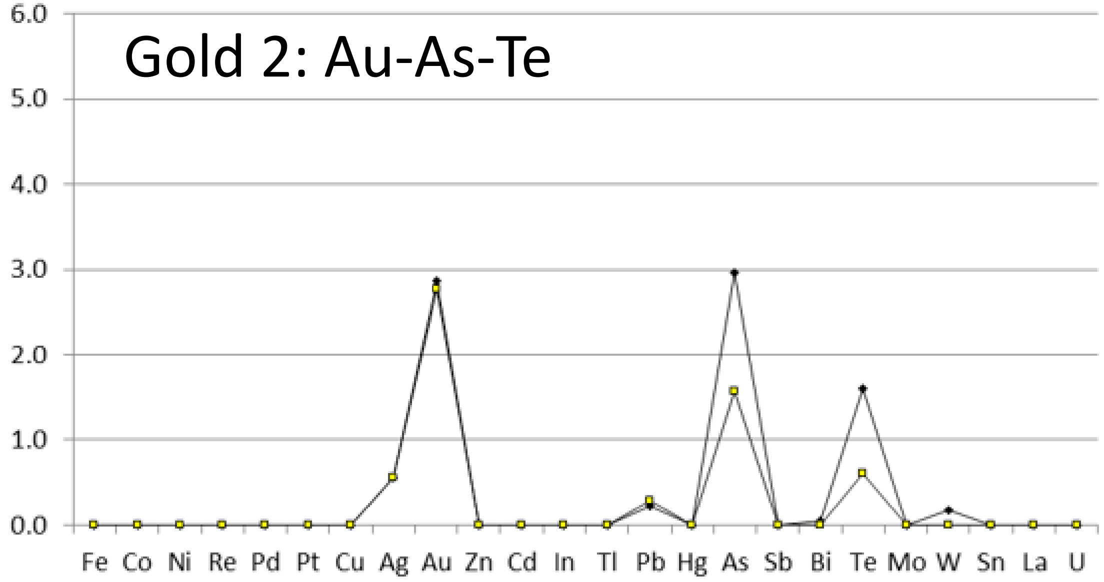
1. **Eigenvector:** How much X plus how much Y, plus ….. (What direction?)
2. **Eigenvalue:** What proportion of overall variation (How long?)
3. **Scaled Eigenvector:** Scaled by eigenvalue. Most useful output of all. Sum of squares for each variable sums to 1.
4. **PC Score:** Principal component score for <u>*individual*</u> samples

PCA Step 4: Interpret Ranked Scaled Eigenvectors



Two Orogenic Gold Signatures





Examples of Gold 1 and Gold 2 ore element signatures on OSNACA Enrichment Diagrams

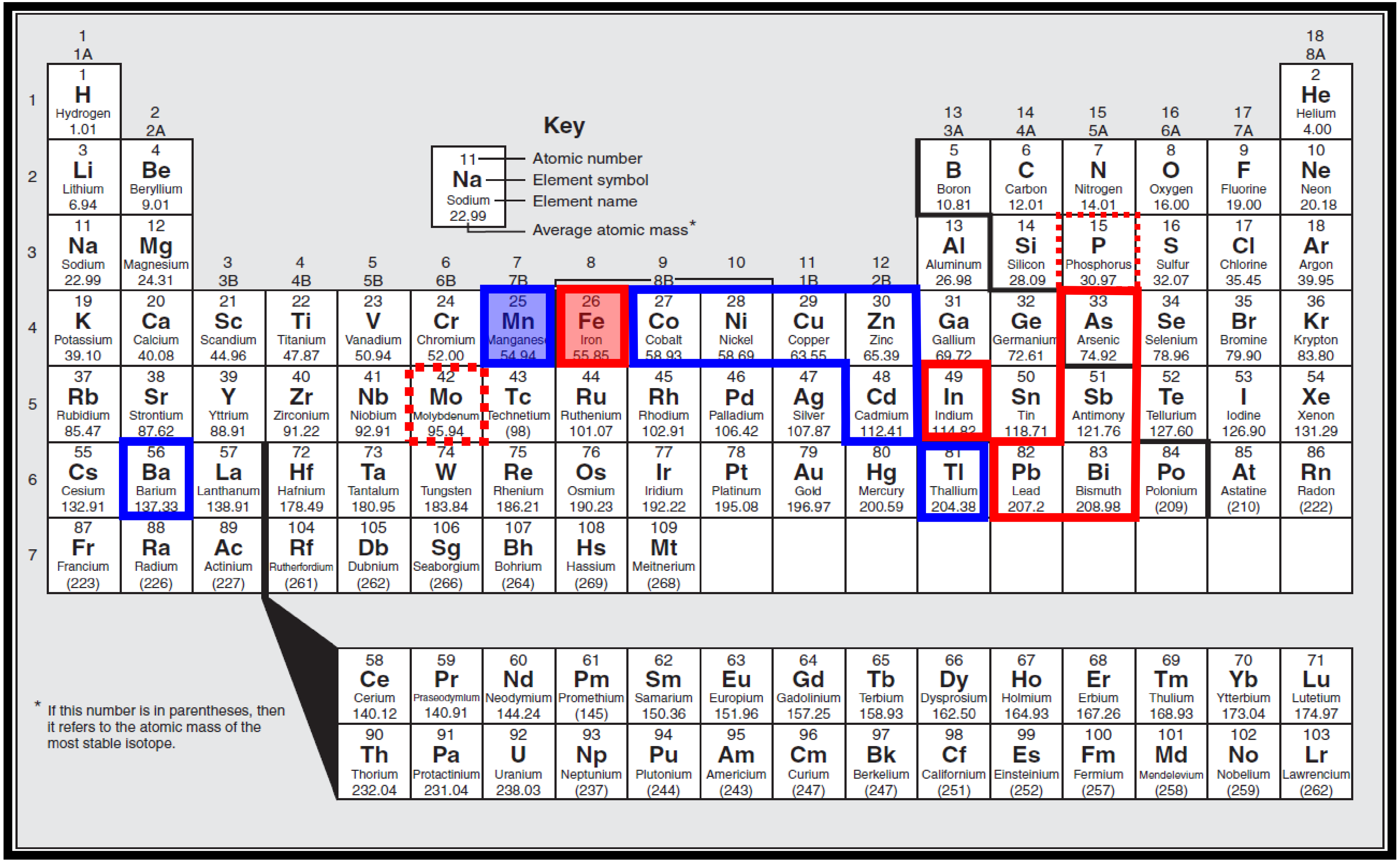
Note: Co, Re, Pd, Pt, In, Tl, U assays not provided

How Has This Helped?

We have rapidly assessed data for 80-odd RC samples from an orogenic gold project and have the following leads to follow up:

- Mafic, felsic and sedimentary host rock signatures have been defined
- Two different styles of gold mineralisation have been identified, one “oxidised”, the other “reduced”. Should we target where these two systems meet?
- White mica alteration may also have been defined and requires follow-up

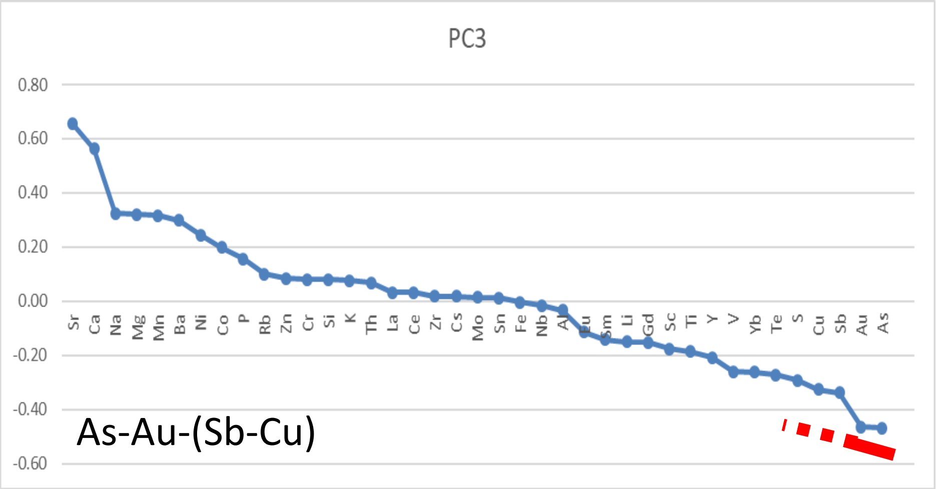
Scavenging


Key
11 Atomic number
Na Element symbol
Sodium Element name
22.99 Average atomic mass*
1 1A
2 2A
3 3B
4 4B
5 5B
6 6B
7 7B
8
9 8B
10
11 1B
12 2B
13 3A
14 4A
15 5A
16 6A
17 7A
18 8A
1 H Hydrogen 1.01
2 He Helium 4.00
3 Li Lithium 6.94
4 Be Beryllium 9.01
5 B Boron 10.81
6 C Carbon 12.01
7 N Nitrogen 14.01
8 O Oxygen 16.00
9 F Fluorine 19.00
10 Ne Neon 20.18
11 Na Sodium 22.99
12 Mg Magnesium 24.31
13 Al Aluminum 26.98
14 Si Silicon 28.09
15 P Phosphorus 30.97
16 S Sulfur 32.07
17 Cl Chlorine 35.45
18 Ar Argon 39.95
19 K Potassium 39.10
20 Ca Calcium 40.08
21 Sc Scandium 44.96
22 Ti Titanium 47.87
23 V Vanadium 50.94
24 Cr Chromium 52.00
25 Mn Manganese 54.94
26 Fe Iron 55.85
27 Co Cobalt 58.93
28 Ni Nickel 58.69
29 Cu Copper 63.55
30 Zn Zinc 65.39
31 Ga Gallium 69.72
32 Ge Germanium 72.61
33 As Arsenic 74.92
34 Se Selenium 78.96
35 Br Bromine 79.90
36 Kr Krypton 83.80
37 Rb Rubidium 85.47
38 Sr Strontium 87.62
39 Y Yttrium 88.91
40 Zr Zirconium 91.22
41 Nb Niobium 92.91
42 Mo Molybdenum 95.94
43 Tc Technetium (98)
44 Ru Ruthenium 101.07
45 Rh Rhodium 102.91
46 Pd Palladium 106.42
47 Ag Silver 107.87
48 Cd Cadmium 112.41
49 In Indium 114.82
50 Sn Tin 118.71
51 Sb Antimony 121.76
52 Te Tellurium 127.60
53 I Iodine 126.90
54 Xe Xenon 131.29
55 Cs Cesium 132.91
56 Ba Barium 137.33
57 La Lanthanum 138.91
72 Hf Hafnium 178.49
73 Ta Tantalum 180.95
74 W Tungsten 183.84
75 Re Rhenium 186.21
76 Os Osmium 190.23
77 Ir Iridium 192.22
78 Pt Platinum 195.08
79 Au Gold 196.97
80 Hg Mercury 200.59
81 Tl Thallium 204.38
82 Pb Lead 207.2
83 Bi Bismuth 208.98
84 Po Polonium (209)
85 At Astatine (210)
86 Rn Radon (222)
87 Fr Francium (223)
88 Ra Radium (226)
89 Ac Actinium (227)
104 Rf Rutherfordium (261)
105 Db Dubnium (262)
106 Sg Seaborgium (266)
107 Bh Bohrium (264)
108 Hs Hassium (269)
109 Mt Meitnerium (268)
58 Ce Cerium 140.12
59 Pr Praseodymium 140.91
60 Nd Neodymium 144.24
61 Pm Promethium (145)
62 Sm Samarium 150.36
63 Eu Europium 151.96
64 Gd Gadolinium 157.25
65 Tb Terbium 158.93
66 Dy Dysprosium 162.50
67 Ho Holmium 164.93
68 Er Erbium 167.26
69 Tm Thulium 168.93
70 Yb Ytterbium 173.04
71 Lu Lutetium 174.97
90 Th Thorium 232.04
91 Pa Protactinium 231.04
92 U Uranium 238.03
93 Np Neptunium (237)
94 Pu Plutonium (244)
95 Am Americium (243)
96 Cm Curium (247)
97 Bk Berkelium (247)
98 Cf Californium (251)
99 Es Einsteinium (252)
100 Fm Fermium (257)
101 Md Mendelevium (258)
102 No Nobelium (259)
103 Lr Lawrencium (262)
* If this number is in parentheses, then it refers to the atomic mass of the most stable isotope.

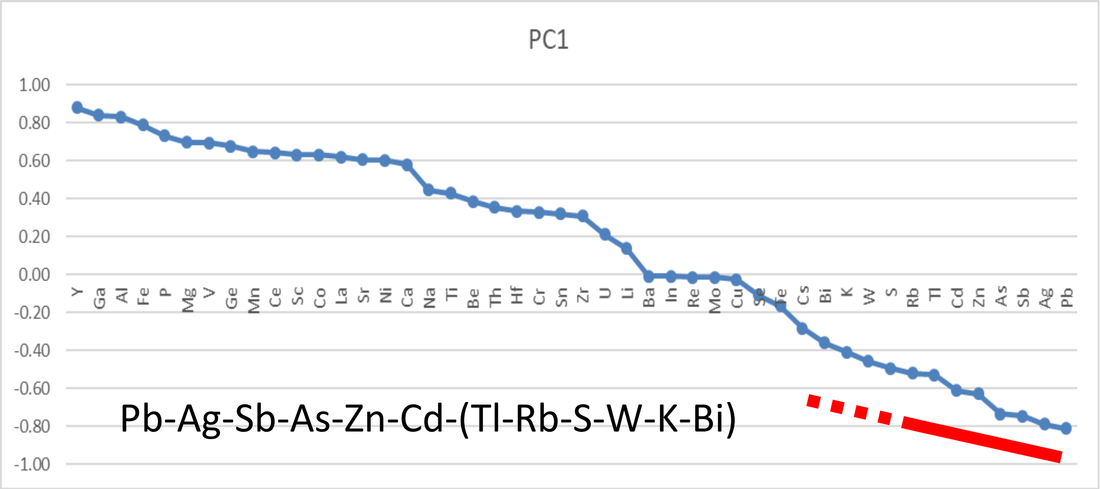
Scale Dependence

Exploration geologists want to isolate metal associations related to mineralisation from everything else. They vary according to scale.

- If detectable in a regional dataset, a mineralisation signal will feature on a lower order PC (e.g., PC5)
- A single point (or maybe a few) will not define a metal association in PCA at all. **<u>You must ALSO look carefully at probability plots.</u>**
- However, within a deposit, a metal signature will feature on PC1

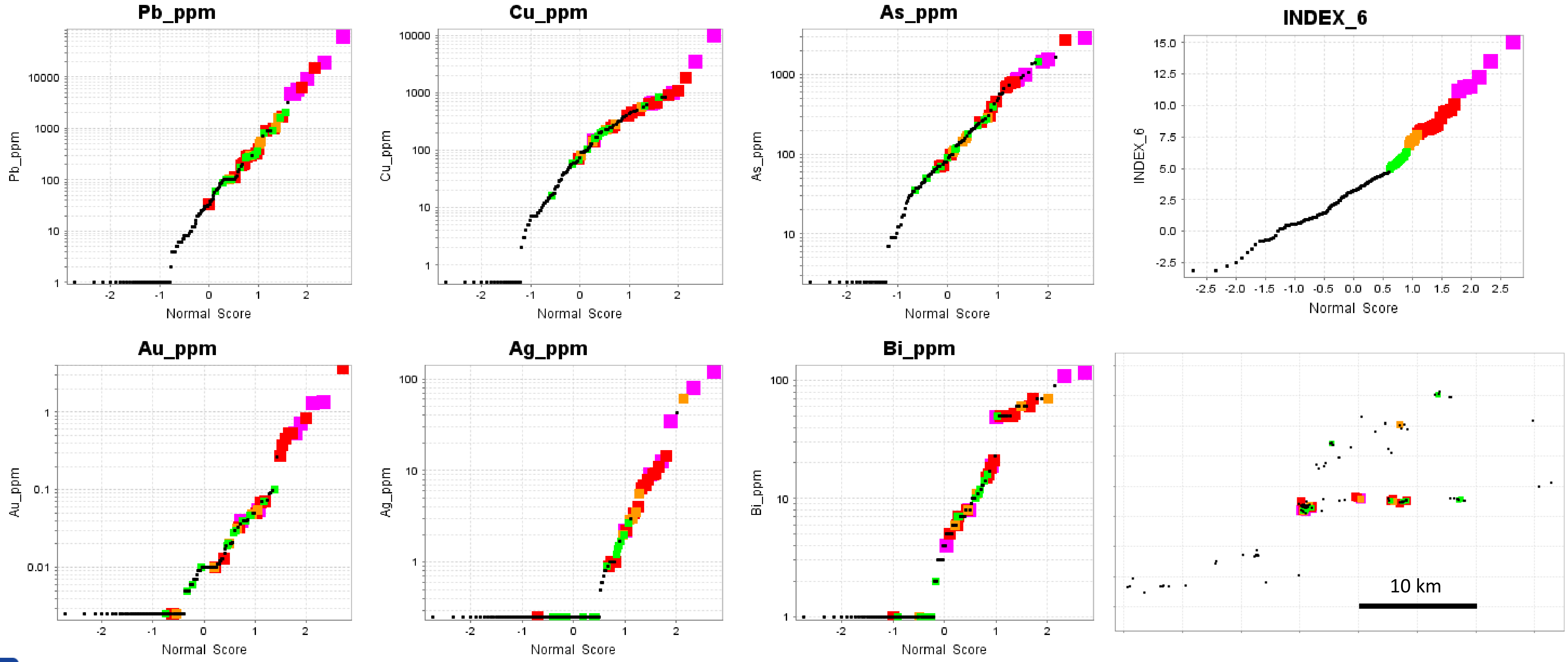


REGIONAL: PC3 or lower



LOCAL: PC1

Additive Indices



Do ***NOT*** use raw values: See also Weighted Sum function in ioGAS

How Has This Helped?

The use of multielement geochemistry to define mineralisation signatures isolates mineralisation from competing processes like regolith and lithology

You should always follow up a Au anomaly with pathfinder support ahead of a Au-only anomaly

The use of multielement geochemistry helps to eliminate false positive and provides more confidence to follow up subtle anomalies that are related to mineralisation

Target ranking is greatly improved

Conclusion

In Mineral Exploration there are THREE main things that whole-rock geochemistry can help us with

1. Lithology
2. Alteration
3. Metal Signatures

1\. is for a more accurate stratigraphic framework → better structure

2\. is for mapping hydrothermal fluid flow → better predicts deposit sites

3\. is for more reliably identifying mineralisation, and having found it, understanding the range of signatures present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Integrating Structural Geology to Understand Mineral Systems

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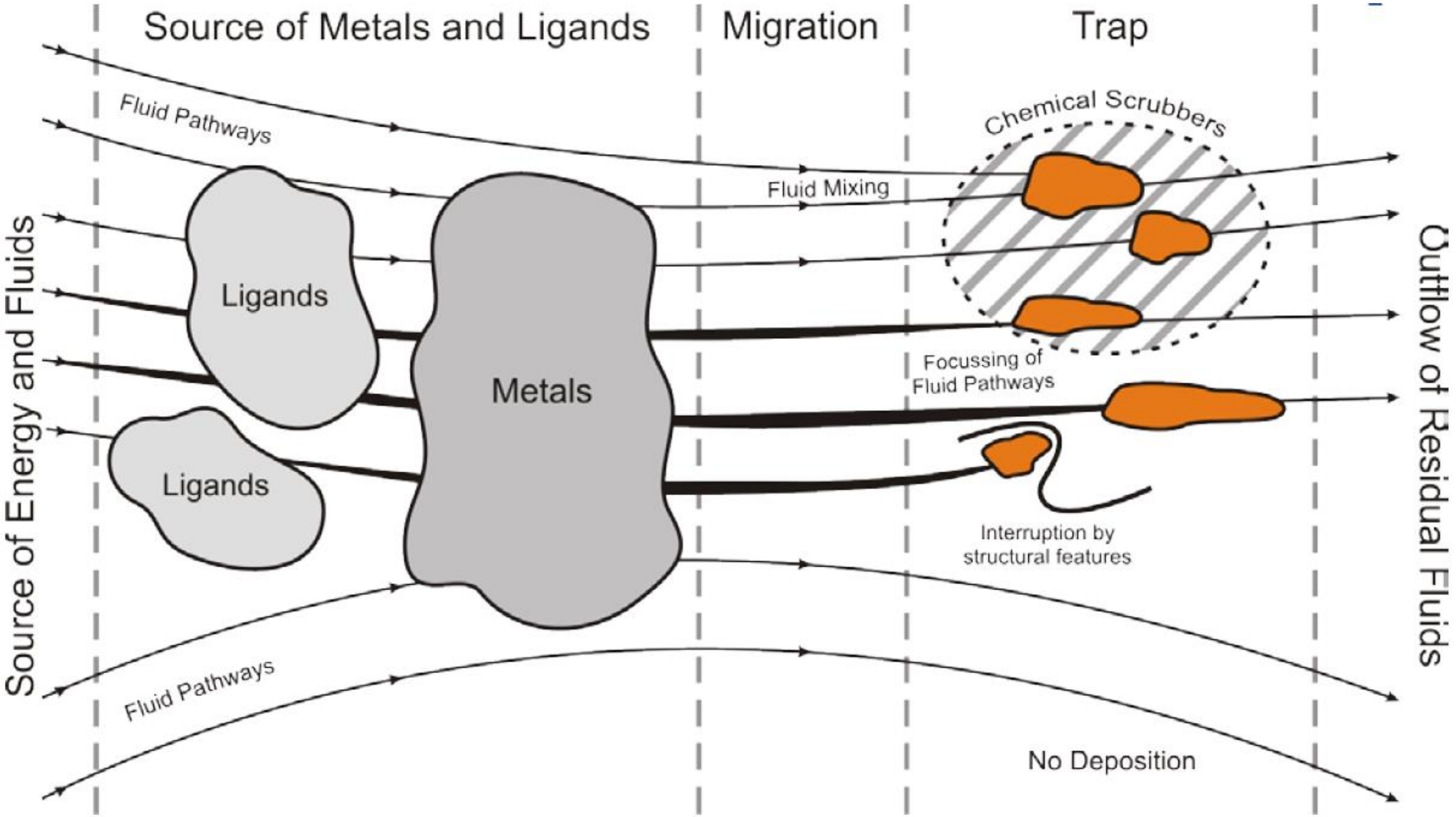
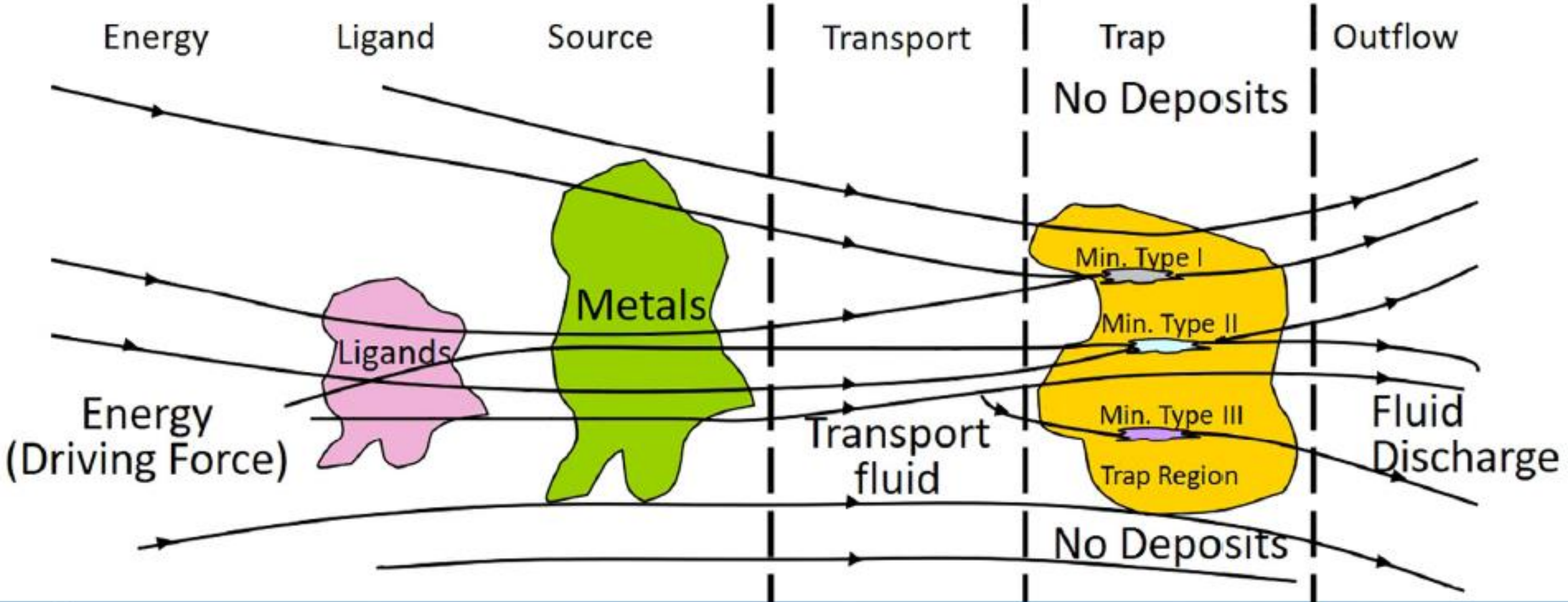
Mineral Systems



Peters et al., 2017; Knox-Robinson and Wyborn, 1997

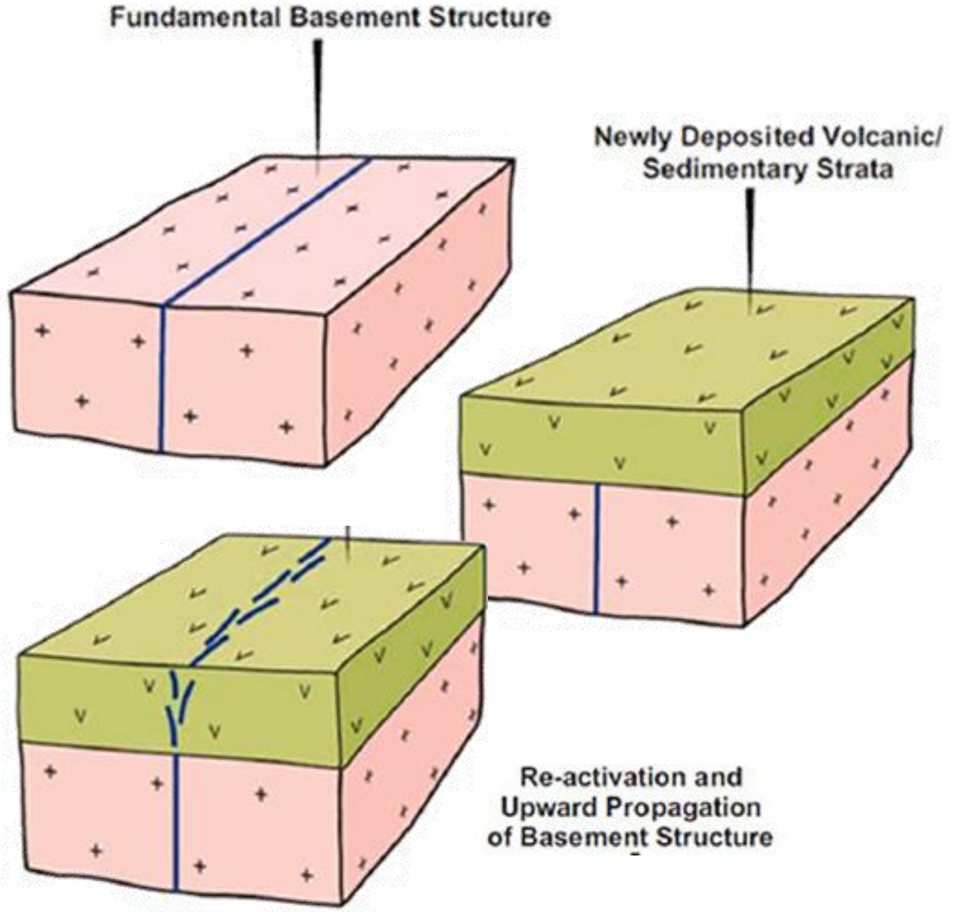
Components of Mineral Systems



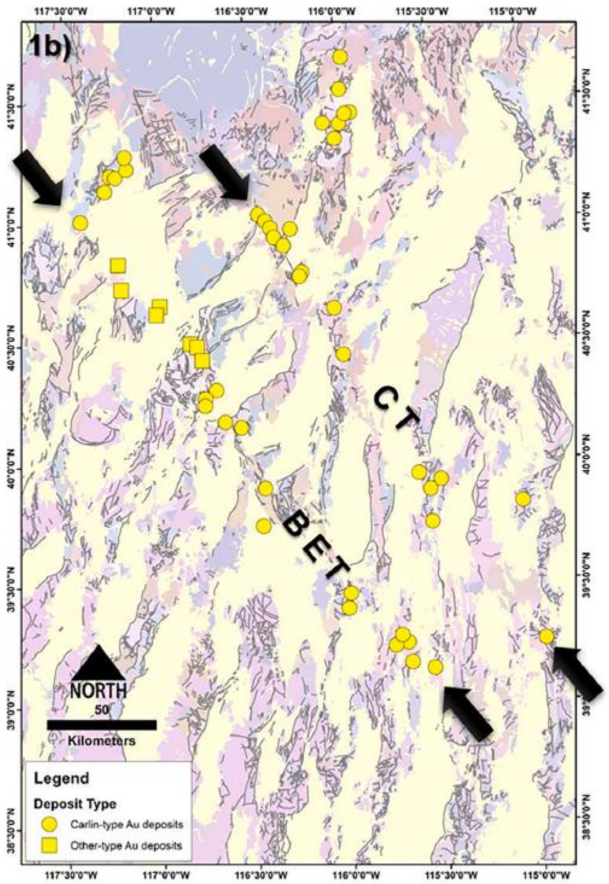
	Energy	Ligand	Source	Transport	Trap	Outflow
MAPPABLE CRITERIA	• Deformation • Metamorphism • Magmatism	• Connate brines • Magmatic fluids • Meteoric fluids	• Enriched source rocks • Magmatic fluids	• Structures • Permeable zones	• Structures • Chemical traps	• Structures • Aquifers
SPATIAL PROXIES	• Metamorphic grade • Igneous intrusions • Sedimentary thickness	• Evaporites • Organics • Isotopes	• Radiometric anomalies • Geochemical anomalies • Whole-rock geochemistry	• Fault/shear zones • Folds • Geophysical/ geochemical anomalies • Alteration	• Dilational traps • Reactive rocks • Geophysical/ geochemical anomalies • Alteration	• Magnetic/ radiometric/ geochemical anomalies • Alteration • Structures

Ford et al., 2019; Knox-Robinson and Wyborn, 1997

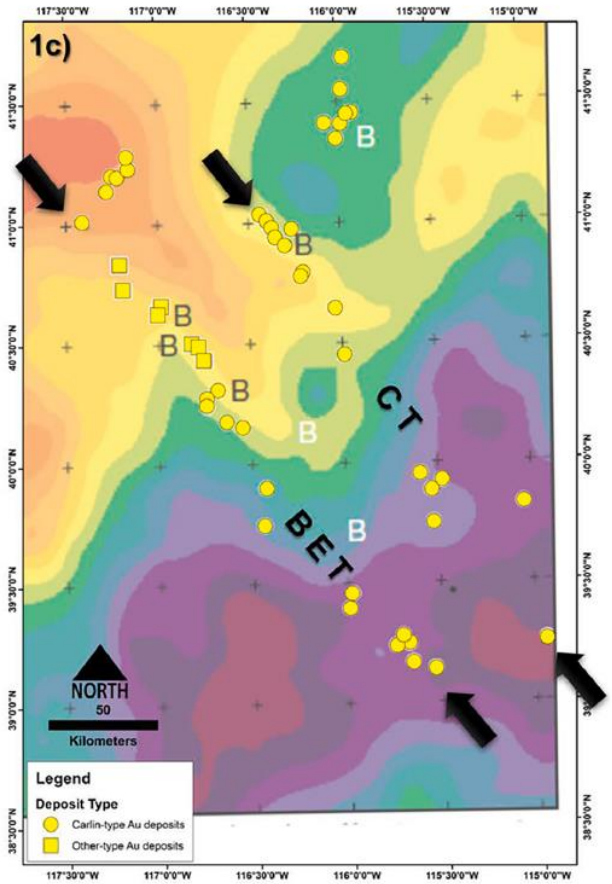
Lithospheric-Scale Structure and Fluid Migration



e.g. Carlin province, Nevada

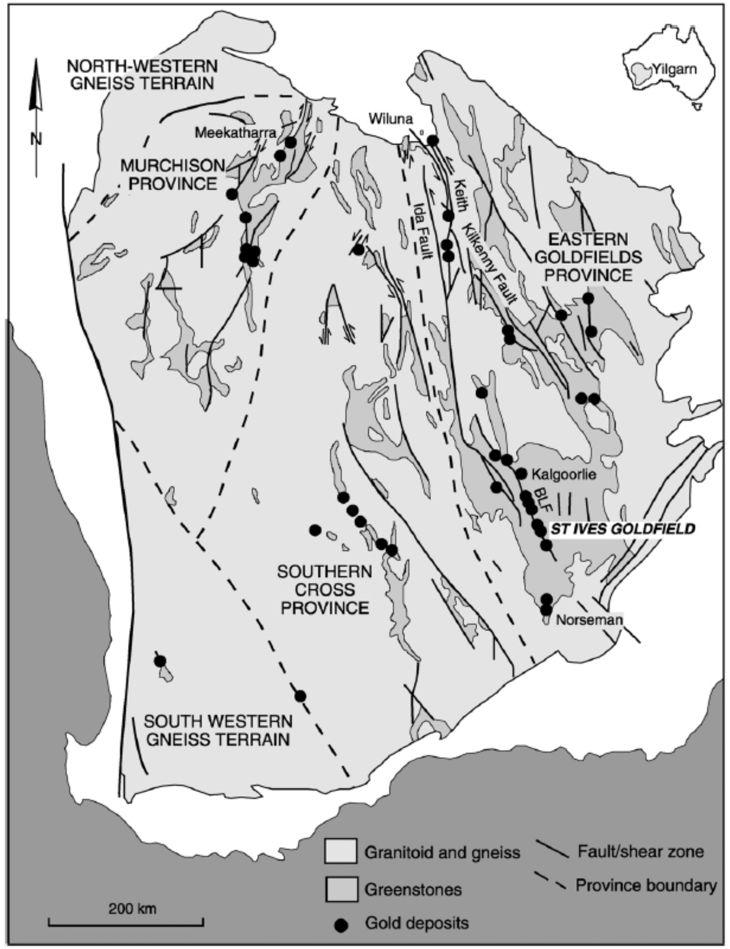


Bouguer Gravity

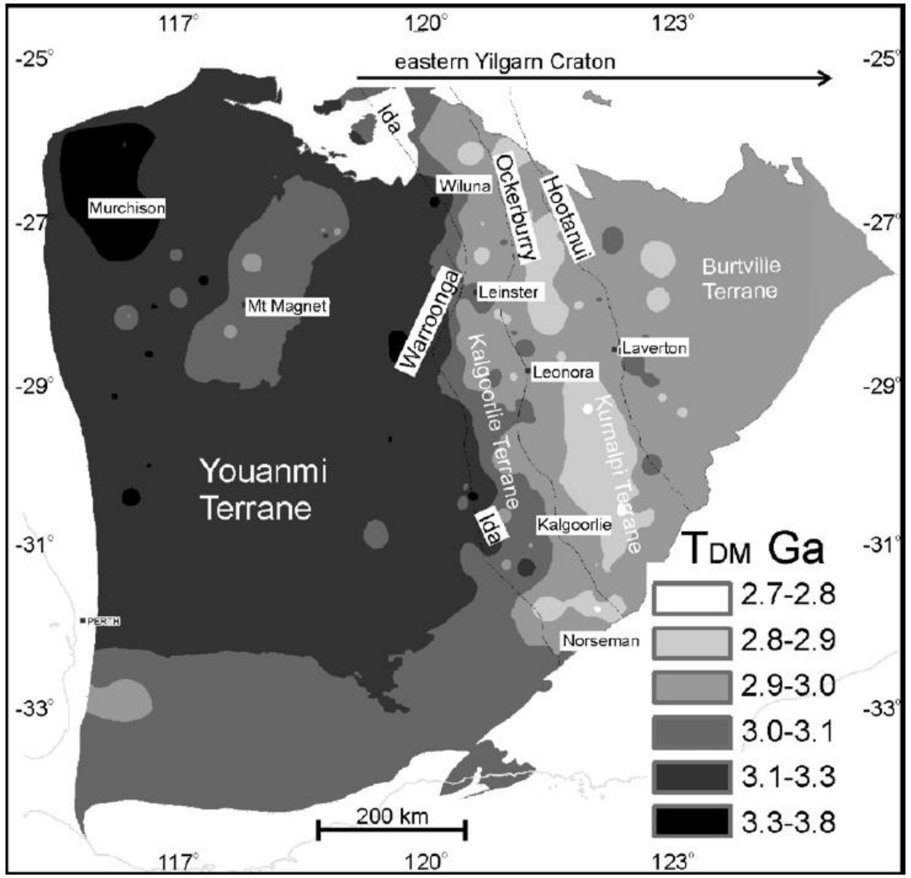


Hronsky and Kreuzer, 2019; McCuaig and Hronsky, 2014

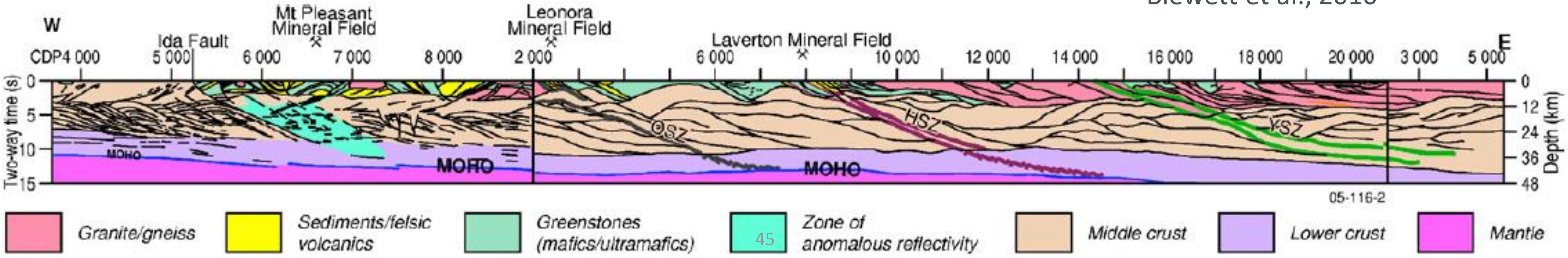
Hronsky and Kreuzer, 2019; Grauch et al., 2003



Cox & Ruming, 2004; Groves et al., 1989

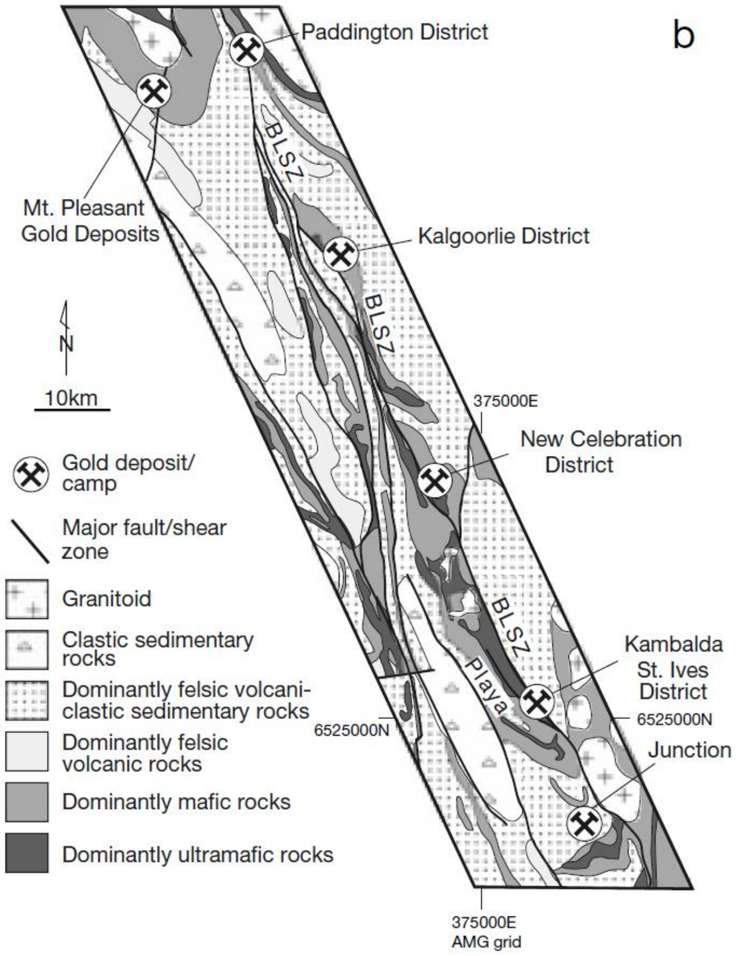


Blewett et al., 2010

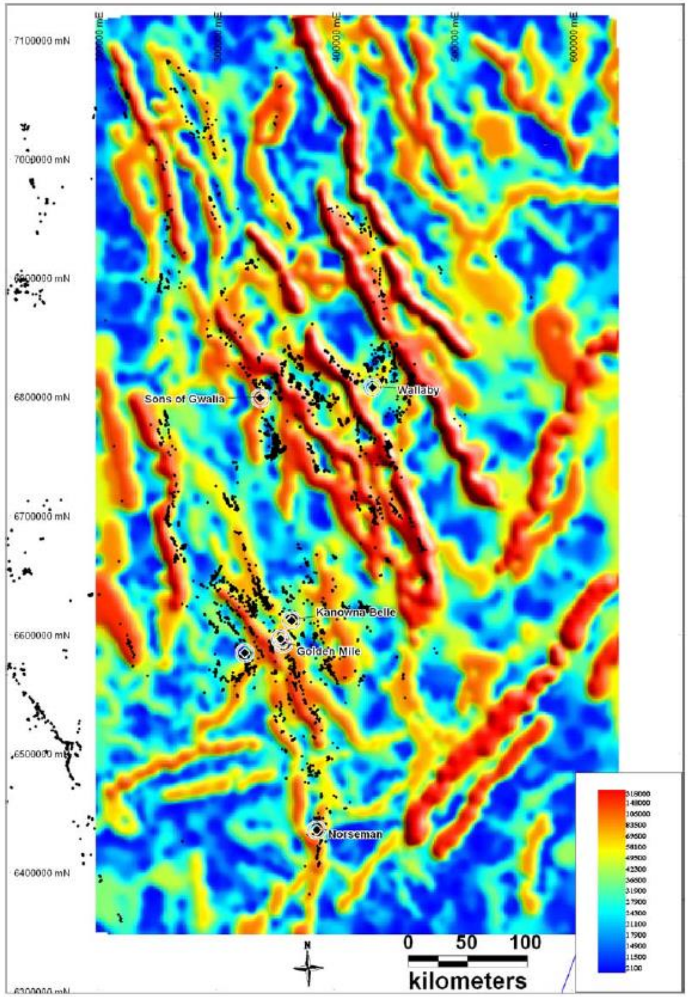


Blewett et al., 2010; Goleby et al., 2003

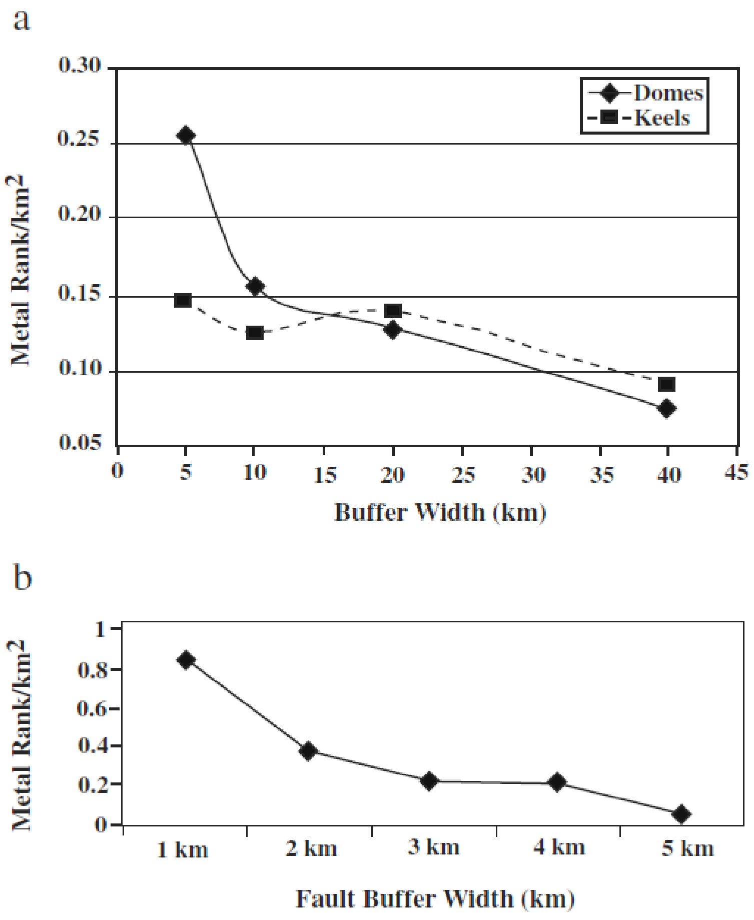
Terrane to Local-Scale Fluid Migration and Trapping



Weinberg et al., 2005

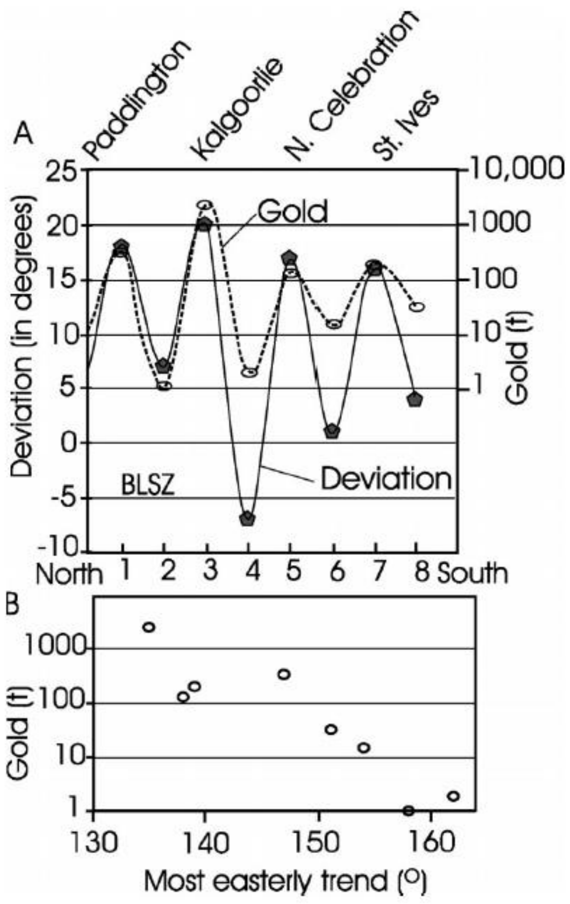


Bierlein et al., 2006

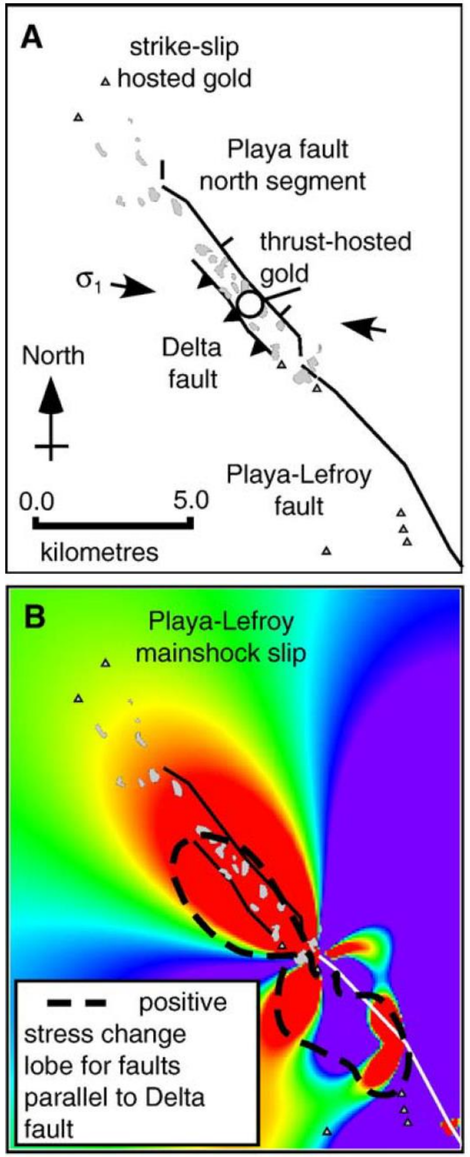


Bierlein et al., 2006

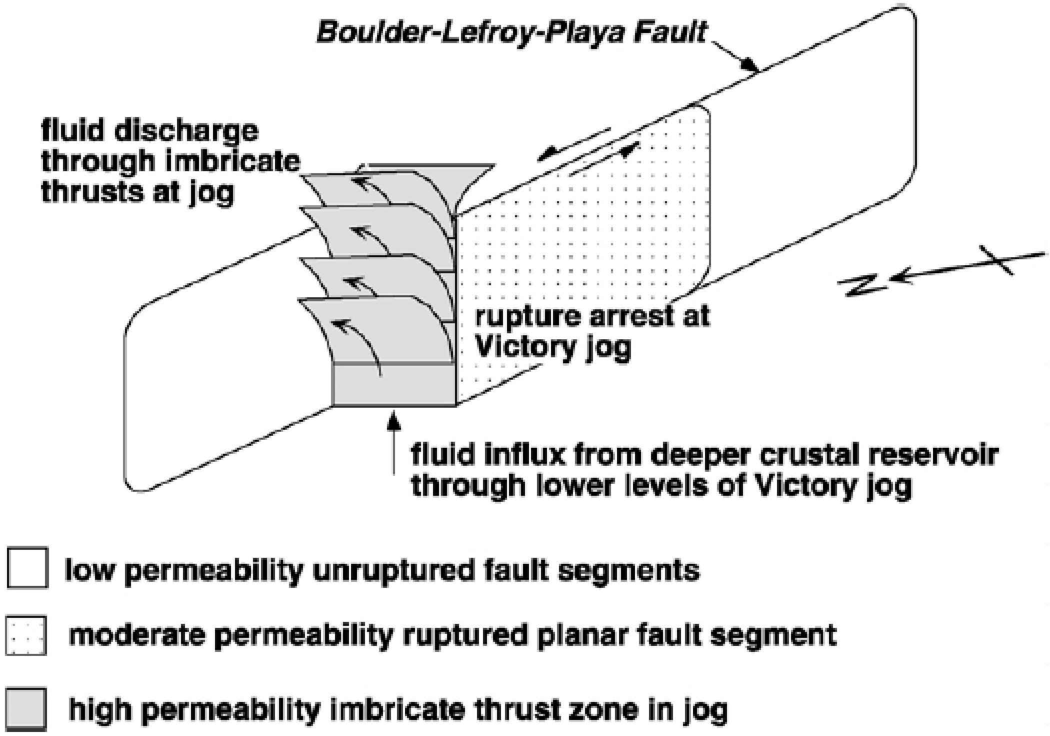
Local to Deposit-Scale Fluid Migration and Trapping



Weinberg et al., 2004

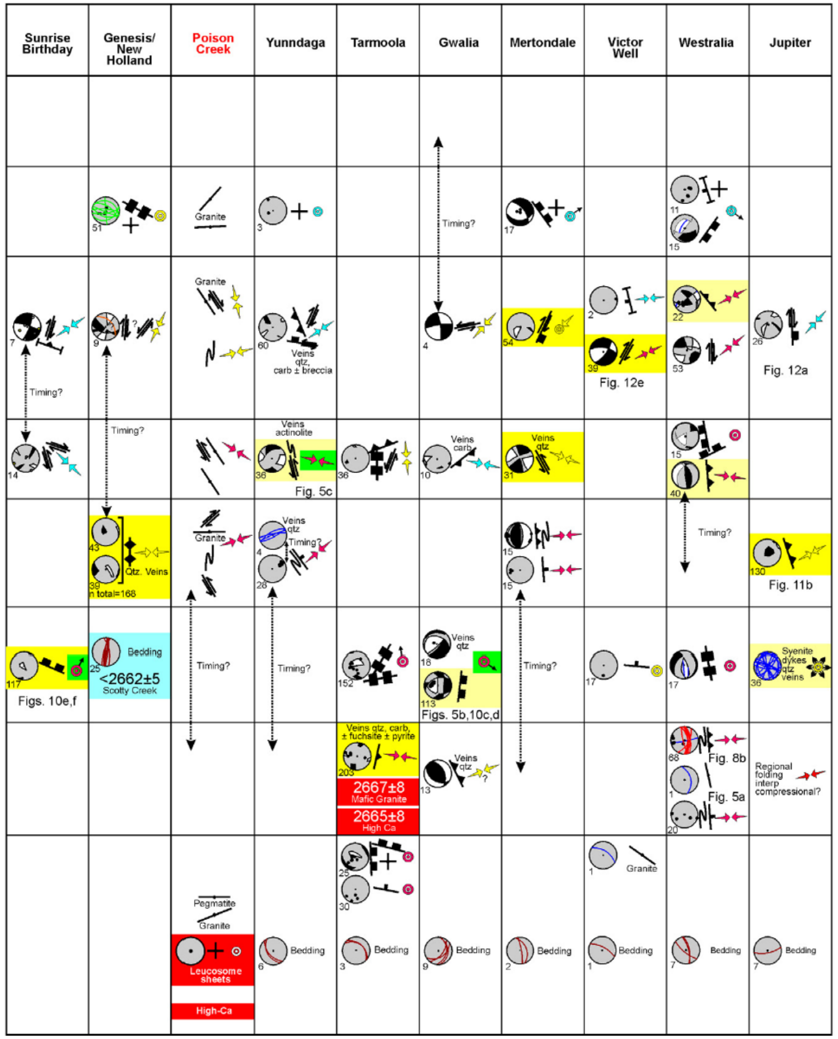


Micklethwaite and Cox, 2006

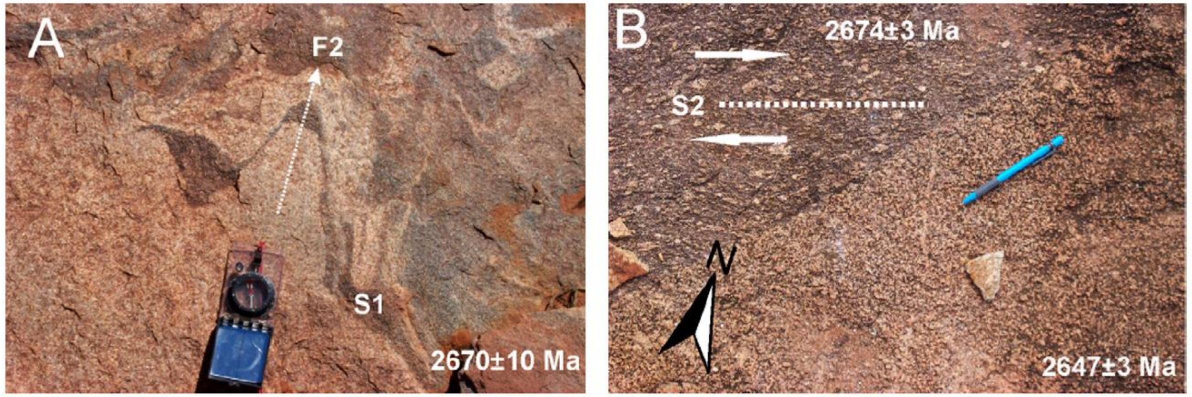


Cox and Ruming, 2004

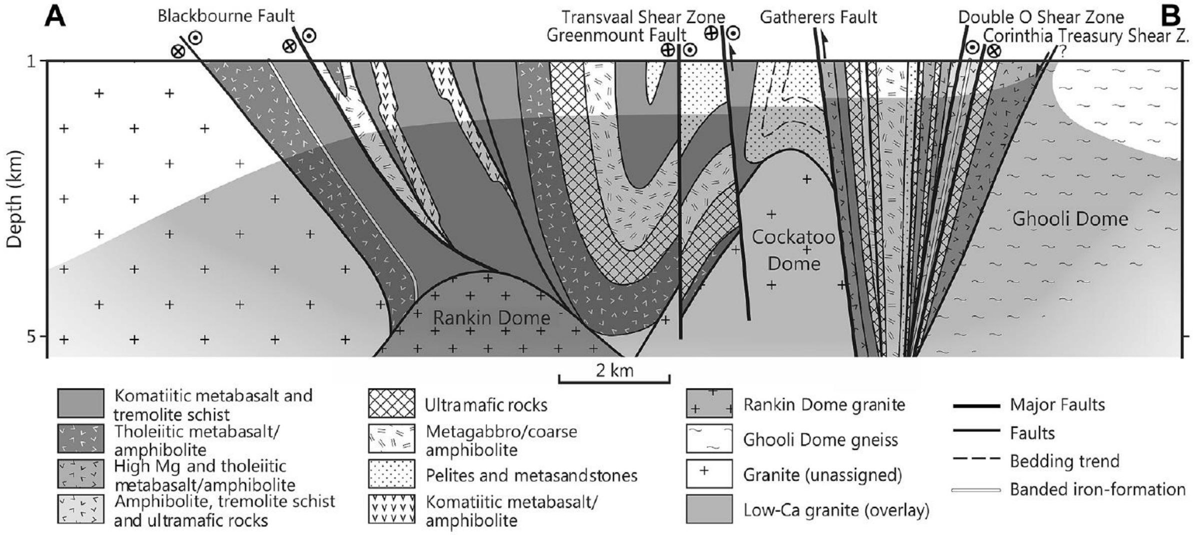
Deposit-Scale Events and Traps?



Blewett et al., 2010



Blewett et al., 2010



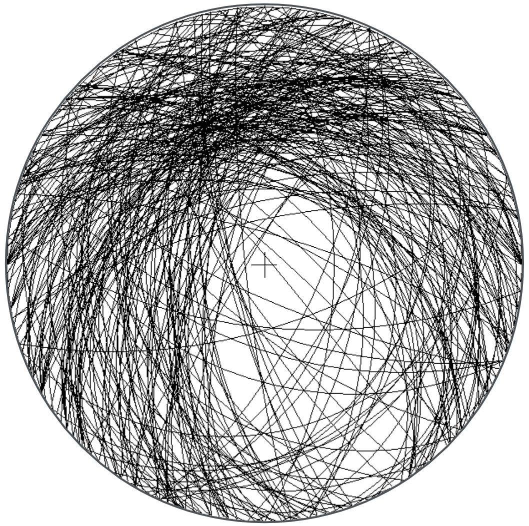
Doublier et al., 2014

Deposit-Scale Events and Traps?

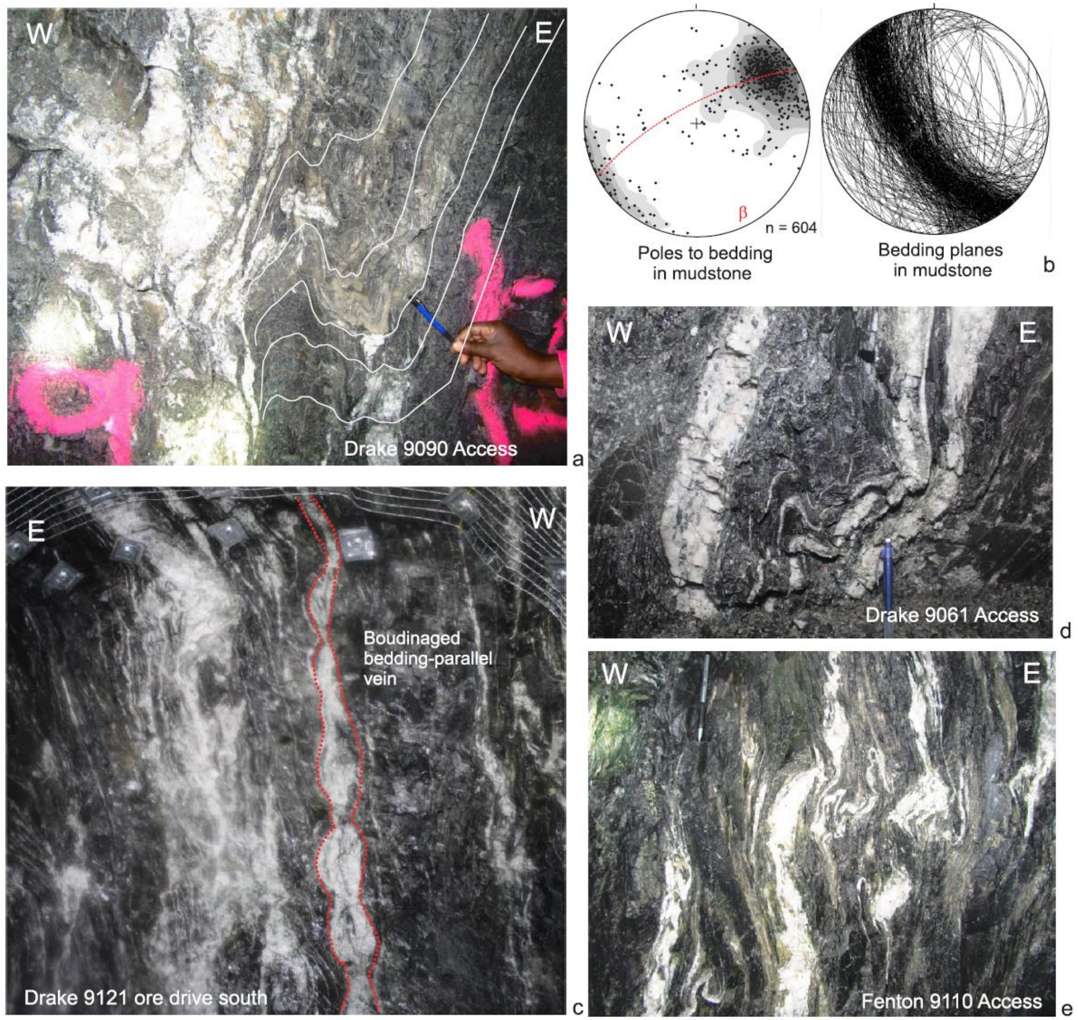
H1000	Hole_id	Depth From	Structure	SPATIAL	Alpha	Beta
D	ULDD019	105.3	BD	O	60	15
D	ULDD019	105.6	BD	O	55	20
D	ULDD019	105.7	BD	O	50	0
D	ULDD019	125.7	FO	O	35	350
D	ULDD019	133.6	FO	O	40	211
D	ULDD019	130.3	FO	O	50	355
D	ULDD019	133.1	VN	O	25	202
D	ULDD019	138.7	VN	O	35	170
D	ULDD019	149.1	FZ	O	55	5
D	ULDD019	149.5	FZ	O	60	35
D	ULDD019	149.7	FZ	O	55	15
D	ULDD019	162	FO	O	47	242
D	ULDD019	162.1	VN	O	70	174
D	ULDD019	163.9	VN	O	65	85
D	ULDD019	164.2	VN	O	50	127
D	ULDD019	163.4	FO	O	60	315
D	ULDD019	165.9	FX	O	35	310
D	ULDD019	164.8	VN	O	45	118
D	ULDD019	166.2	FO	O	15	137
D	ULDD019	166.2	JS	O	60	100
D	ULDD019	166.8	JS	O	50	225
D	ULDD019	169.4	FO	O	40	355
D	ULDD019	170	FZ	O	50	90

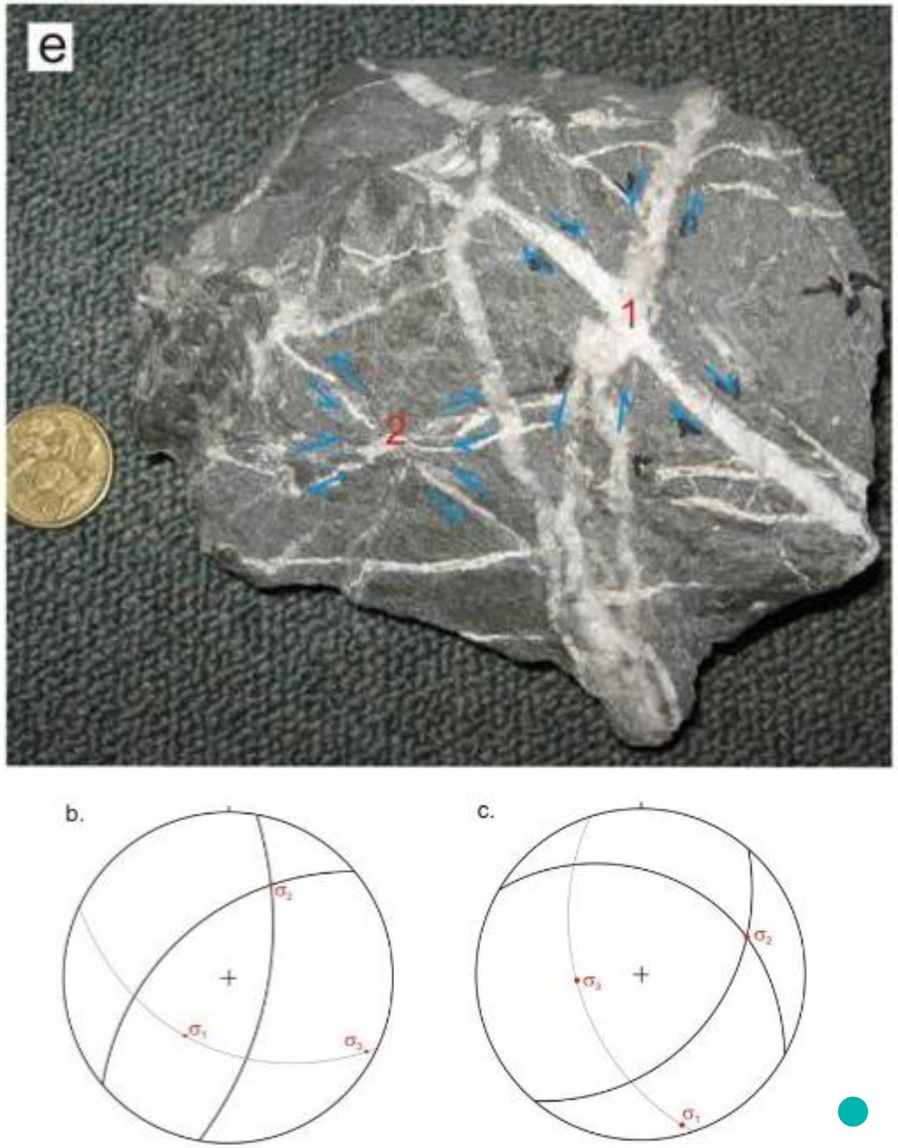
We cant rely on orientation alone to distinguish important structures and orientations.

We need more than this from our data collection.



Deposit-Scale Structural Observations

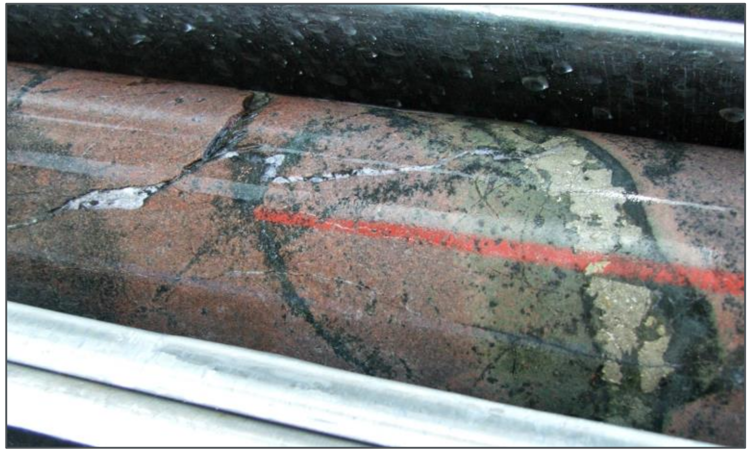




Jones et al., 2019

Deposit-Scale Structural Observations

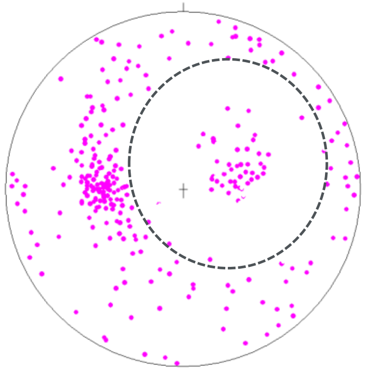
- Focus on observations rather than interpretation.
- What are the key characteristics of structures we can use to classify and interpret them.
- Make observations "Queryable“.
- Get observations out of the comments field and into the data fields.
- Recording of cross-cutting relationships are key to interpret timing.

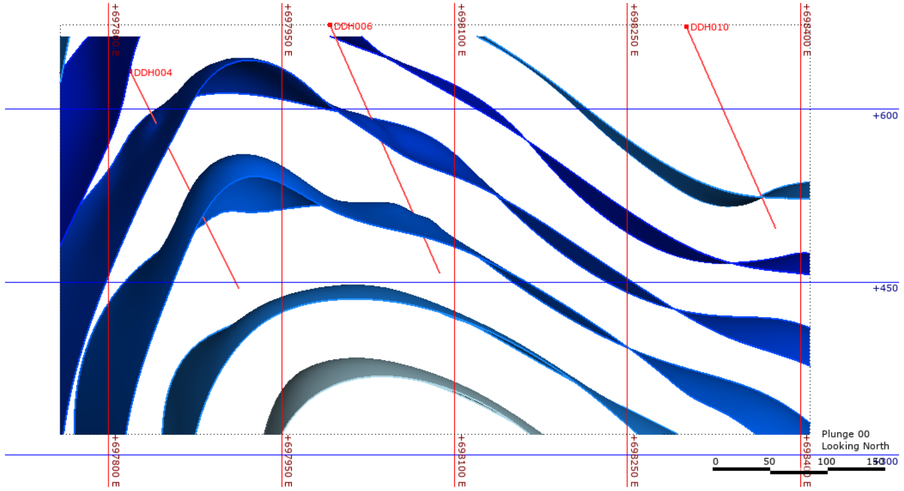


Quality Control of Structural Observations

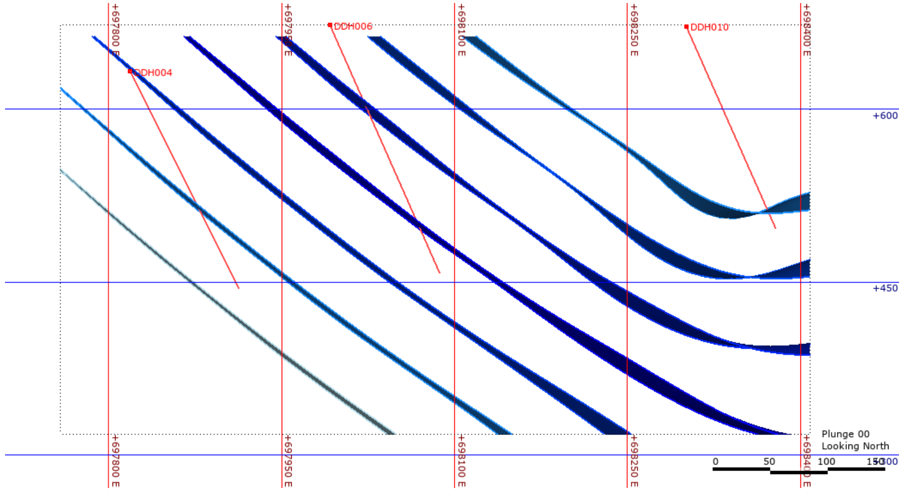
In all stages of core orientation, mark up and measurement, accuracy is key. Record the confidence associated with different workflows.

The accumulation of small errors over multiple stages can result in significant errors that can affect the quality of results.





Non filtered bedding data
Apparent folding (which is not real!)



Filtered, good bedding data

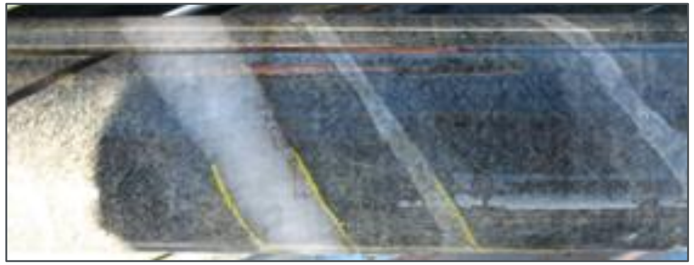
Is a Vein Just a Vein?

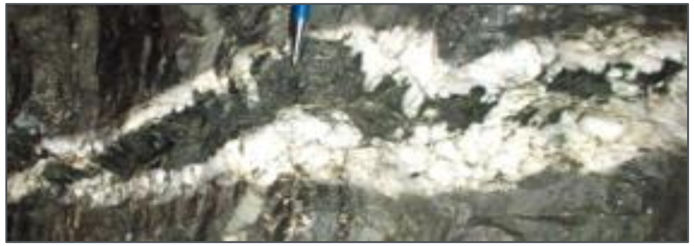
Veins need to be separated for structural analysis by their characteristics, as well as their orientation and mineralogy.

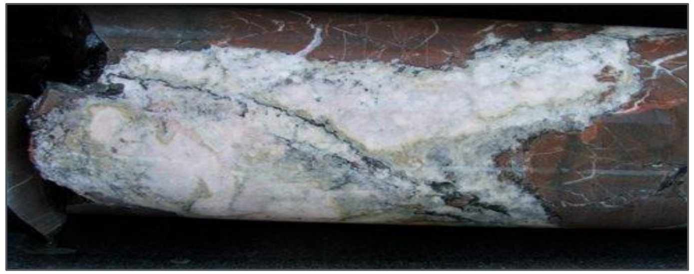
For example, the vein characteristic could describe:

- What does the vein look like internally?
- What is the shape of the vein?
- How does the vein relate to other similar veins?

Vein abundance is important, but you don't have to measure every vein. Quantify similar veins by recording frequency.

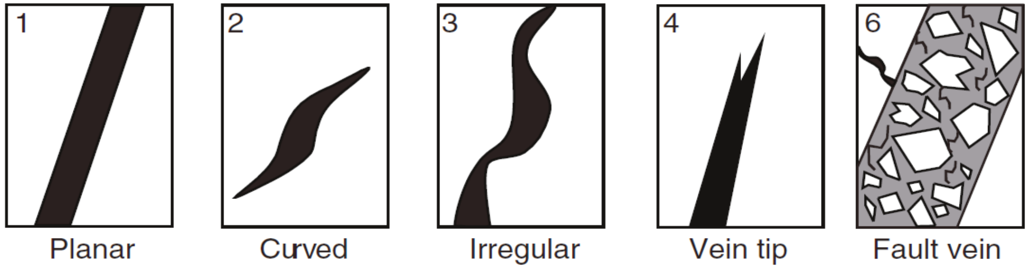




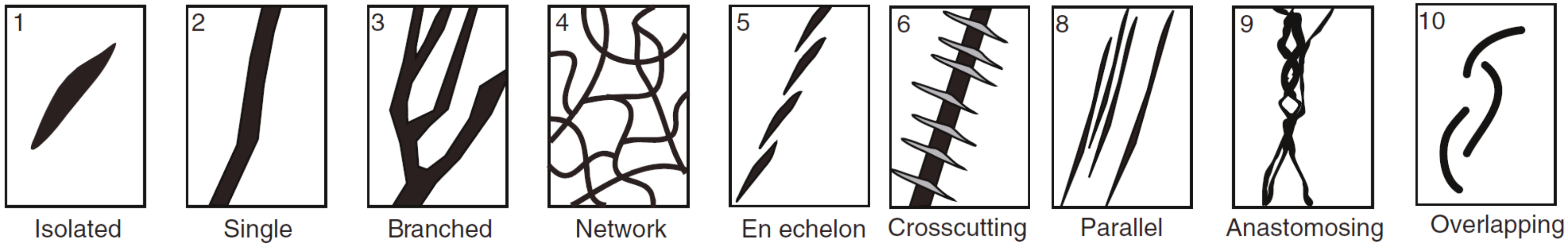


Is a Vein Just a Vein?

Vein Morphology



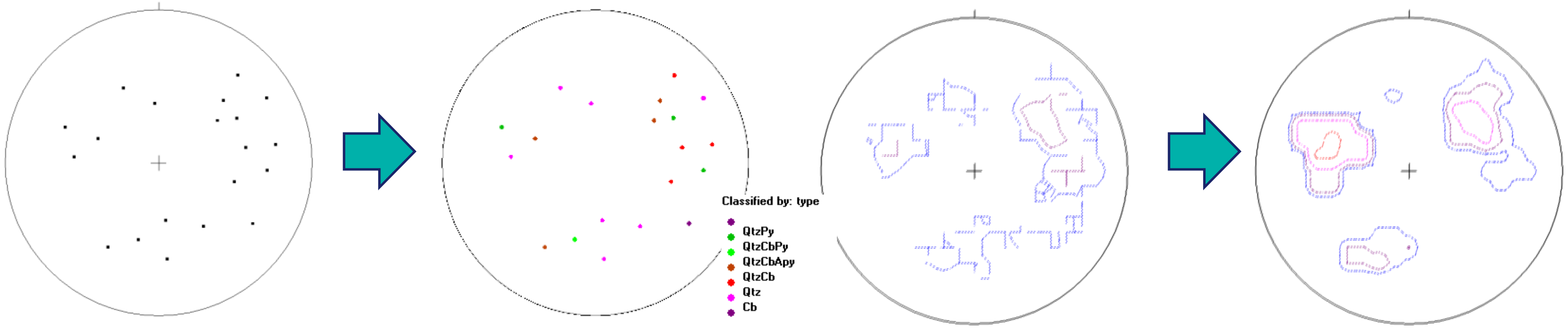
Vein Connectivity



All Veins
Not very helpful or useful

Veins by composition
Helpful, but not statistically useful

Veins by composition + frequency
Helpful, and statistically useful



What About Other Structures? Faults, Folds, etc, etc

Breccias

Angular

Sub-angular

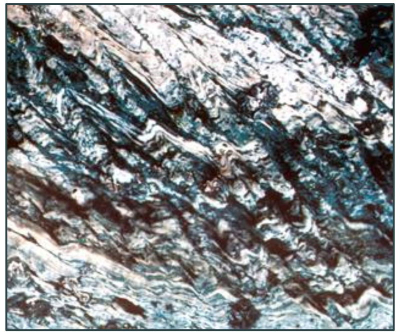
Sub-rounded

Rounded

Foliation

Slaty Cleavage

Crenulation Cleavage



Gneissic Banding

Lineations

Structural Intersections

Fault Slickenfibres

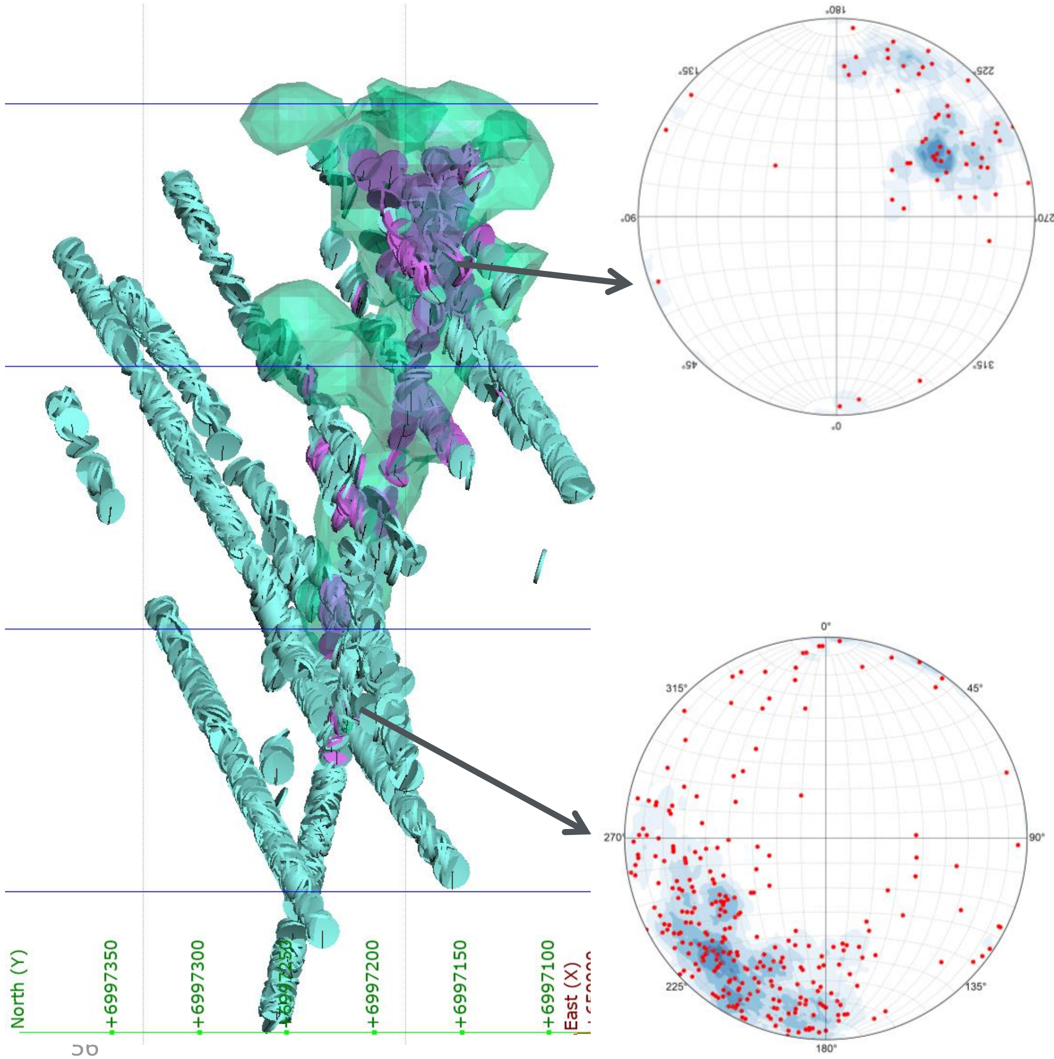
Fold Axis

Migration Pathways, Traps and Mineralisation

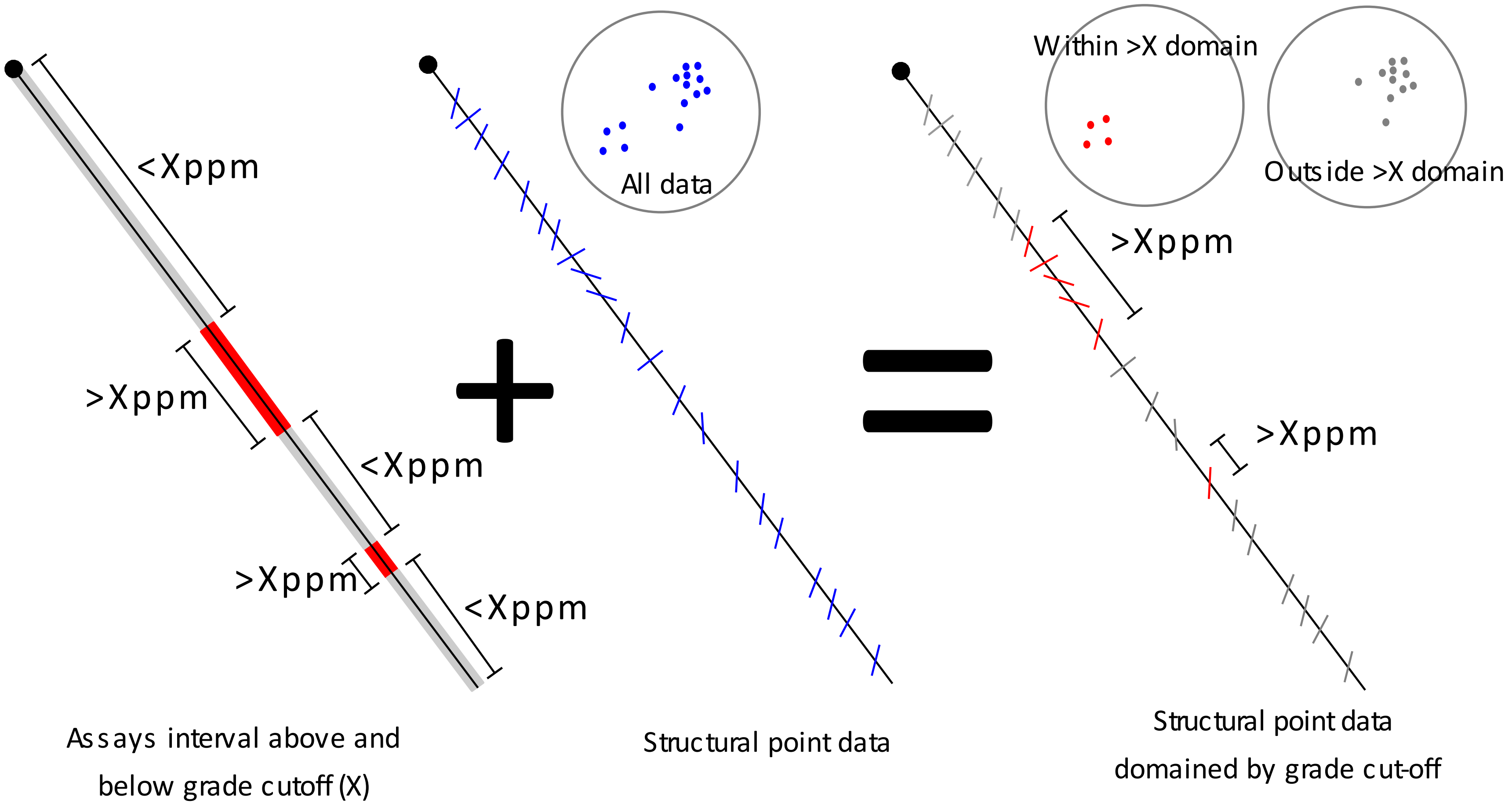
What is different about sites that host mineralisation compared to everything else around it?

Like any other data set (e.g. lithology, geochemistry, geophysics), we are looking for a structural anomaly that may help to predict sites of mineralisation.

> <u>Spatial domaining</u> – domain by fault block, lithology, northing, easting etc. to recognise differences in statistical relationships between structures.



Migration Pathways, Traps and Mineralisation



Working Towards a Mineral System Understanding

Once you have a dataset interpretations can be undertaken for mineral systems understanding:

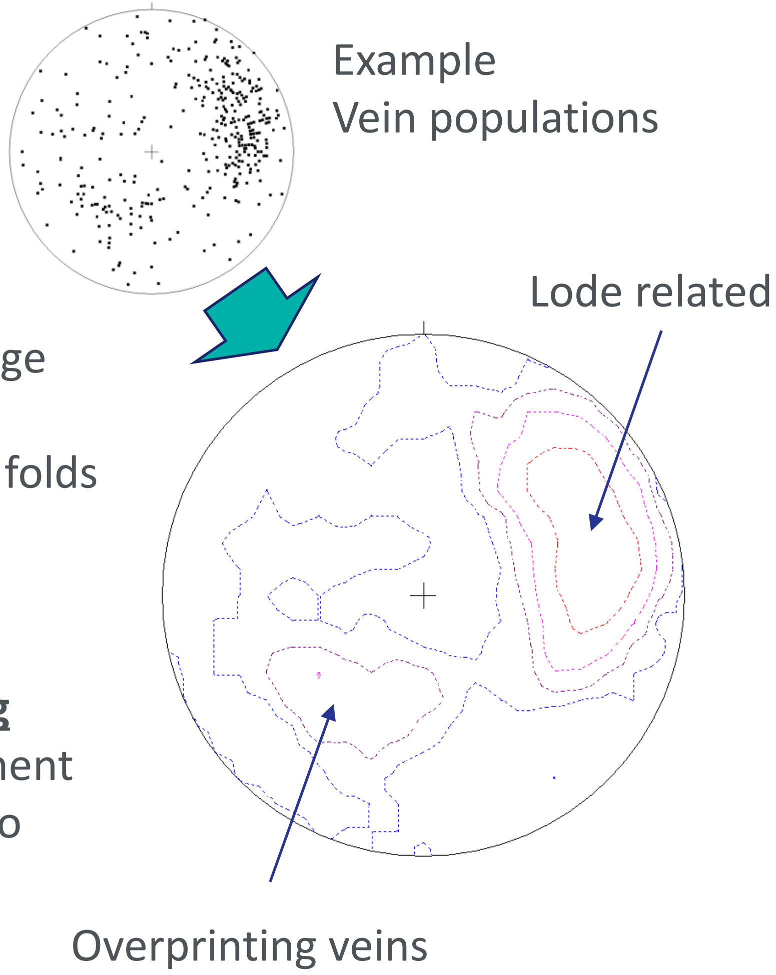
Pre-Mineralisation Architecture	Fold architecture Fault architecture
Syn-Mineralisation dilation/fluid focussing	Faulting/shearing Fault Bends Fault stepovers Structural intersections
Post-Mineralisation deformation/ dismemberment	Folding Faulting/shearing

Folds

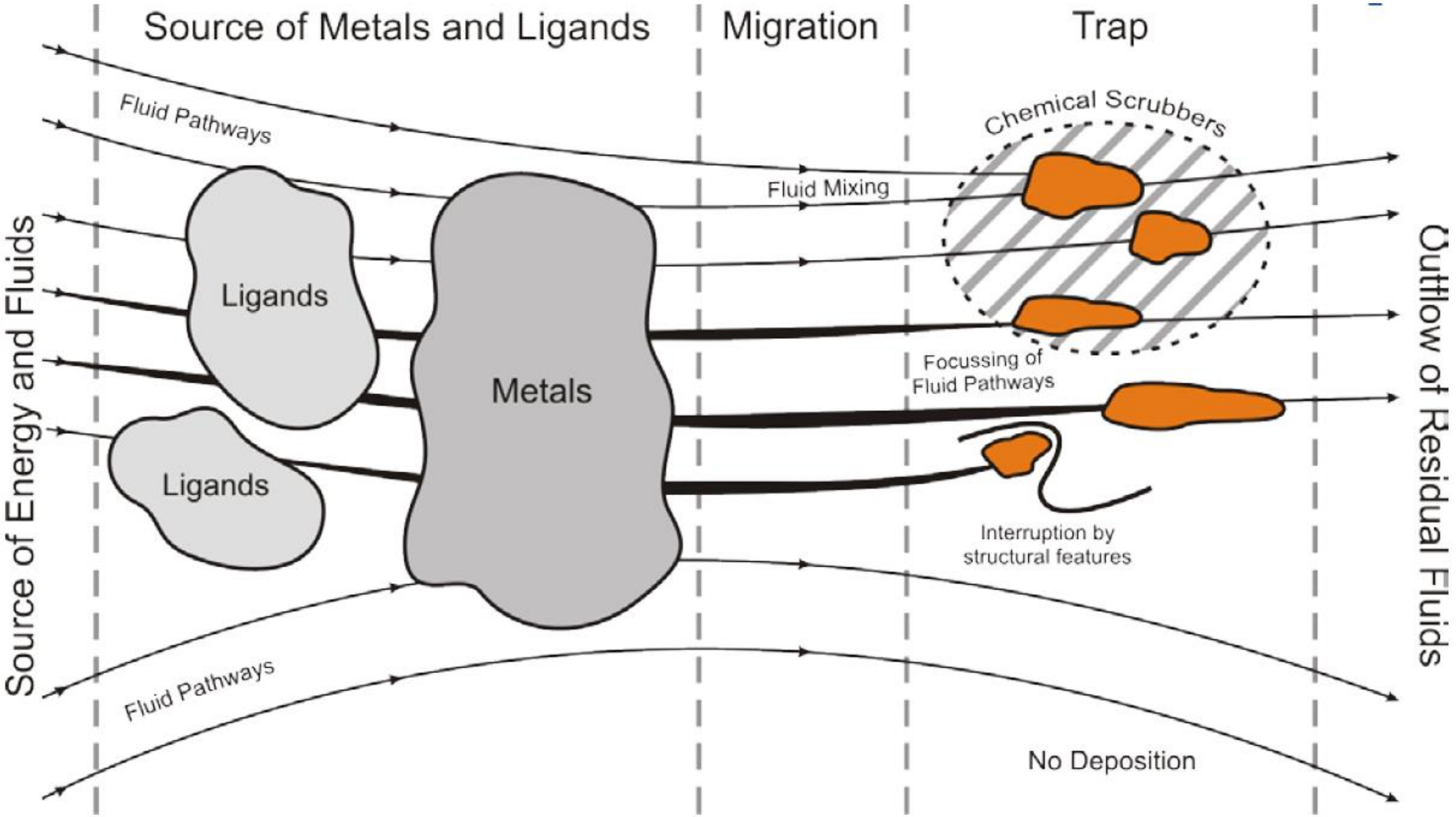
- Plunge and plunge direction
- Position around folds (vergence)
- Style of folding

Faults and shearing

- Sense of movement
- Characteristics to recognise sets



Structural Geology in Mineral Systems



Peters et al., 2017; Knox-Robinson and Wyborn, 1997

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Principles of Structural Data Collection and Controls

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