TERRACORE

GEOSPECTRAL IMAGING

Hyperspectral Core Imaging for Porphyry Deposits

- Porphyry deposits are the main source of the world's copper and molybdenum production, with a significant contribution to gold, silver and base metals

- These deposits are related to plate margin processes, principally subduction, and so occur in well-defined belts. Most economic deposits are relatively young, but porphyry deposits are recognized all the way back to the Archaean. As they are formed at fairly shallow depths, preservation of older deposits is less likely

- Mineralization is associated with large felsic intrusive bodies, late metal enriched hydrothermal fluids are exsolved which form classic porphyry style mineralization in both magmas of the parent intrusive (often high level dykes) as well as country rocks

- Alteration has been well described and refined over the past five decades, with early Na-Ca overprinted by potassic (generally mineralized) in the core of the system and associated propylitic alteration more distally. As the system evolves quartz-sericite and sericite chlorite overprint potassic alteration. In some cases late low temperature argillic and advanced argillic alteration can also overprint earlier alteration (either due to tectonic telescoping or to a closed system that doesn't allow escape of late fluids)

- Porphyry systems generally form from multiple pulses of magma, and so a complex alteration history may be present that can be tricky to unravel

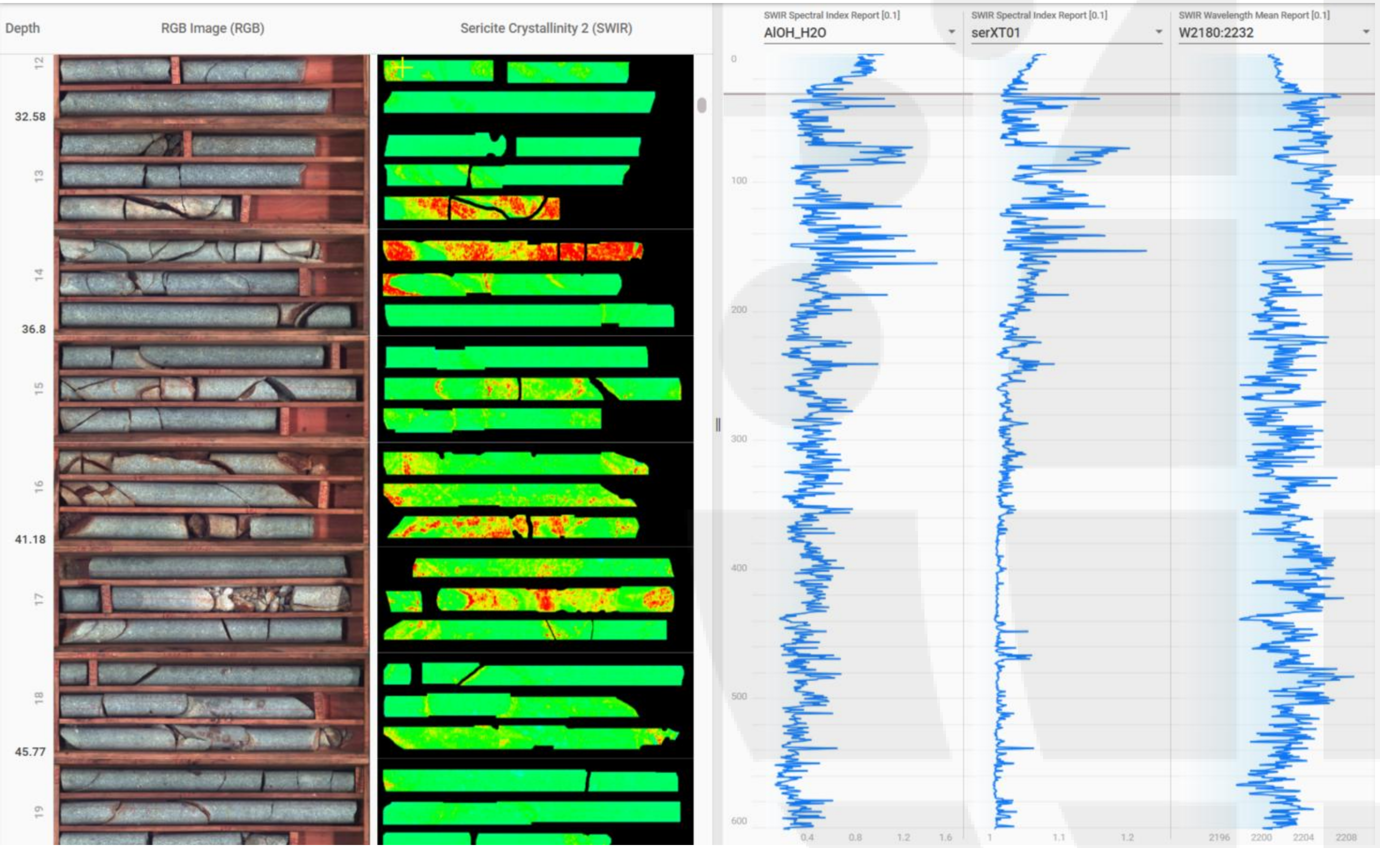
Introduction

- Hyperspectral core imaging is of particular value given:
  - It captures alteration mineralogy in situ and so textural relationships can be easily seen and mapped
  - Since every pixel is imaged, quantitative counts of alteration minerals can be extracted (spectral modal mineralogy). The addition of the long-wave infrared adds anhydrous silicates, crucially calc-silicate minerals
  - By extracting information related to absorptions (SWIR) or peaks (LWIR) the relative strength of spectral response provides a proxy for mineral abundance
  - And by extracting absorption or peak positions, and shifts in those positions, the chemistry of alteration minerals can be examined and mapped
  - By compositing the data, truly representative downhole plots can be output at any desired resolution

Hyperspectral Core Imaging

- There is a good body of literature on the use of spectroscopy in porphyry systems, mainly VN-SWIR using handheld (point) instruments. Of course, the use of imaging retrieves the textural context of alteration minerals
- Many of the alteration minerals, such as biotite (potassic), gypsum (potassic), white mica (quartz-sericite), chlorite (sericite-chlorite and propylitic), amphibole (propylitic and Na-Ca), carbonate (propylitic), and clay minerals (argillic and advanced argillic) are active in the SWIR
- The LWIR is certainly a useful addition, adding K-feldspar (potassic), quartz (widespread) and albite (Na-Ca) to the mapping
- In terms of the SWIR minerals, information about composition (e.g. white micas Si-Al and biotite Mg-Fe) can be of key importance for both vectoring and unravelling the alteration history
- Also of importance is temperature information that can be retrieved from mineral crystallinities. In particular micas aid in vectoring; as well as clay mineralogy that is dependent on pH
- The spectral information is of major importance to geometallurgical modelling providing ore body knowledge. As these deposits are bulk tonnage and low grade, ensuring the right economics is a critical undertaking

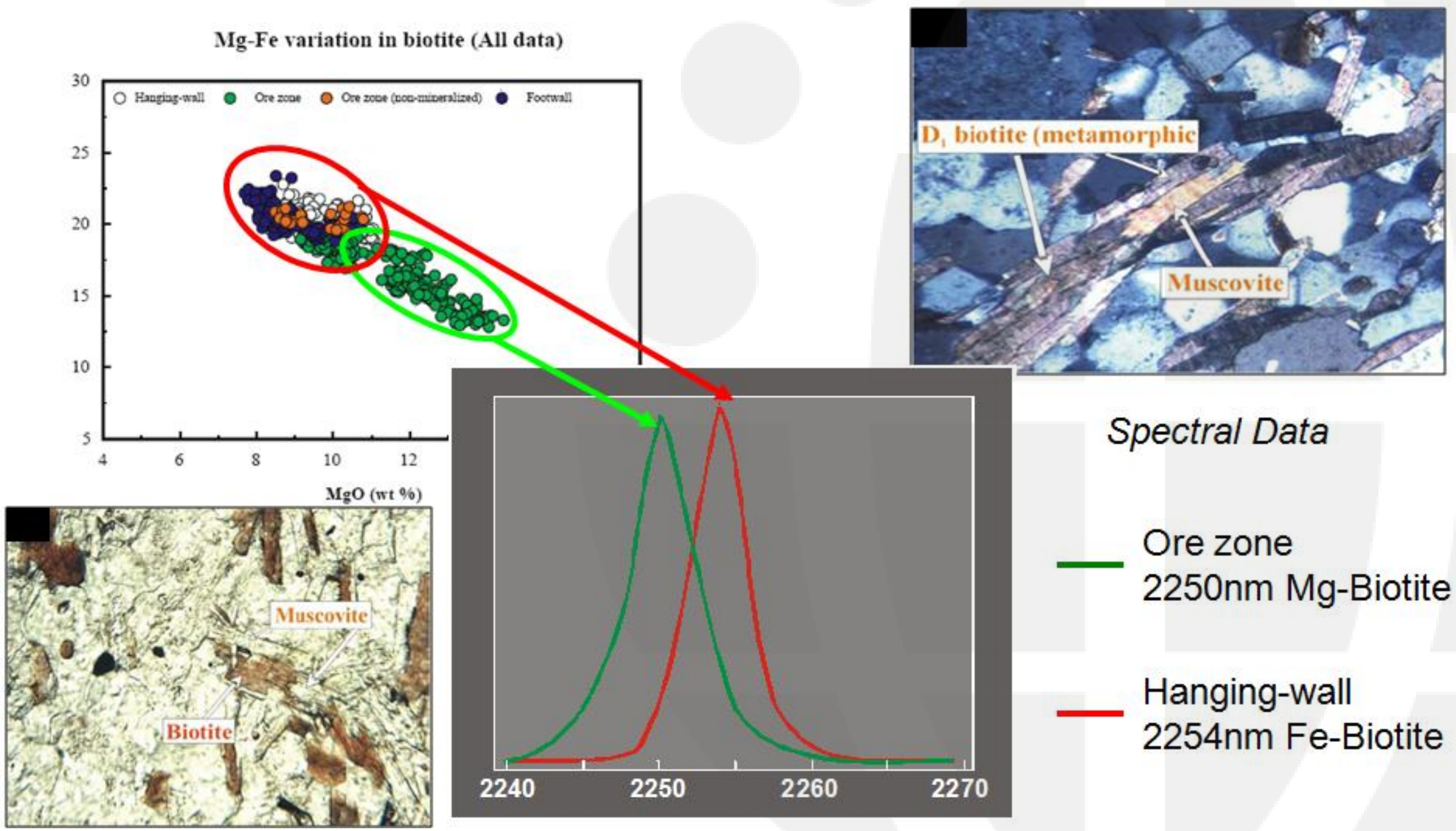
Hyperspectral Responses within Porphyry Systems



- The plots on the left show whitemica crystallinity and composition for an entire drillhole. Two measures have been plotted for crystallinity, one using the ratio of the Al-OH feature to bound water (AlOH_H2O) and the other the shape of the AlOH feature (serXT01)
- These show that the hole has started in high crystallinity mica, which reflects higher temperatures and so is at or close to the core of the system. From about 200 metres depth it passes into lower crystallinity mica, distal to the system's core
- This is accompanied by a subtle change in composition from potassic (muscovitic) in the high crystallinity zone to more Al-rich lower down, which is typical of porphyry systems
- The image shows the textural expression of crystallinity, which is clearly highest within and close to fluid conduits

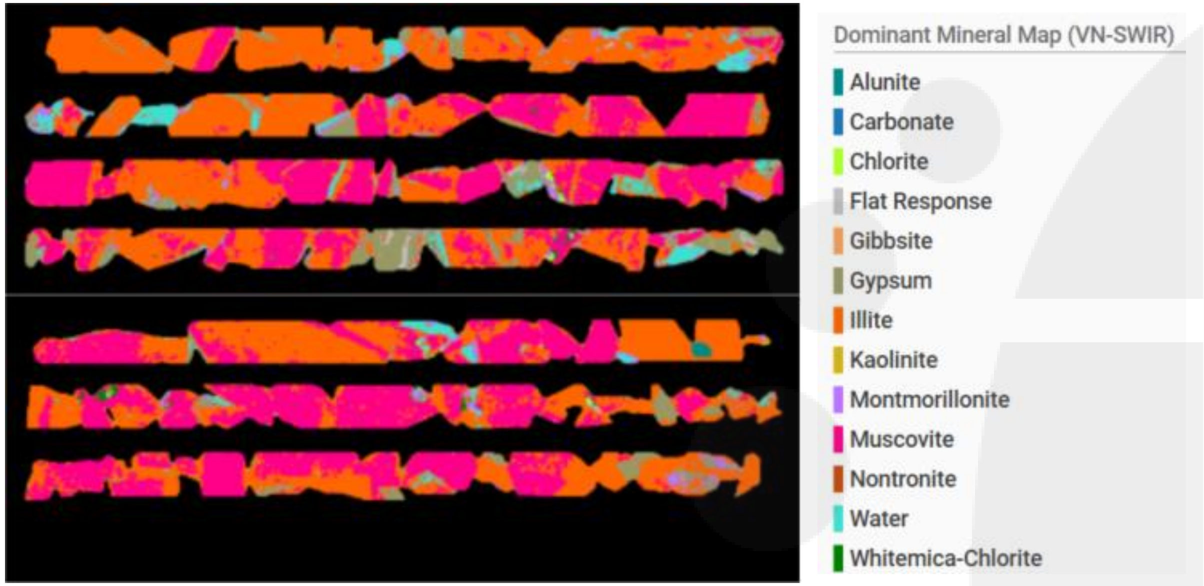
White Mica Composition and Crystallinity

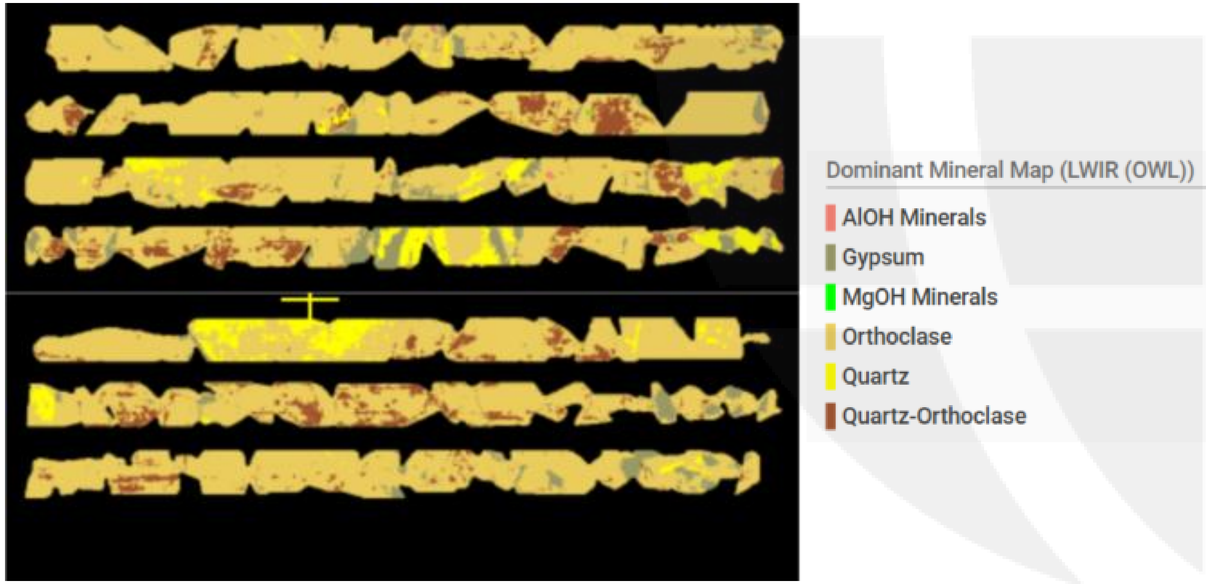
Biotite Composition



- Biotite composition can be inferred from subtle shifts in both the Fe-OH and Mg-OH absorptions; variation in the ~2250nm Fe-OH absorption is shown on the left
- During sulphide mineralization, Fe partitions preferentially into sulphide phases. This causes alteration minerals that form syn-mineralization to be relatively Fe deficient
- Biotite is a common alteration phase in the potassic alteration zone, and shifts towards a more phlogopitic (Mg-rich) composition occur as illustrated

Potassic Alteration





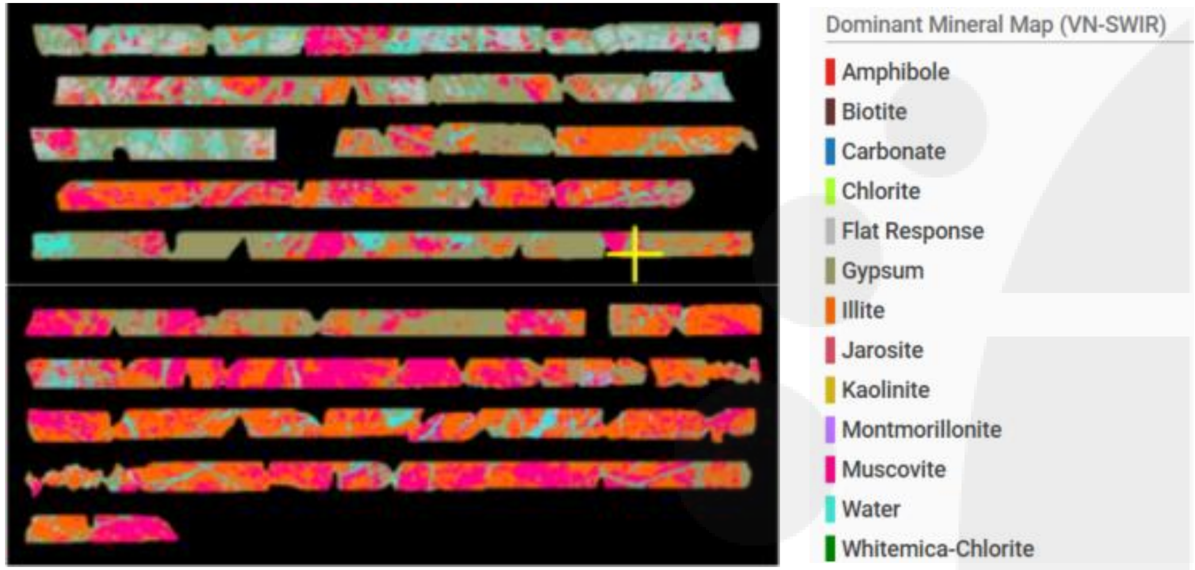
- The example on the left shows a section through potassic alteration

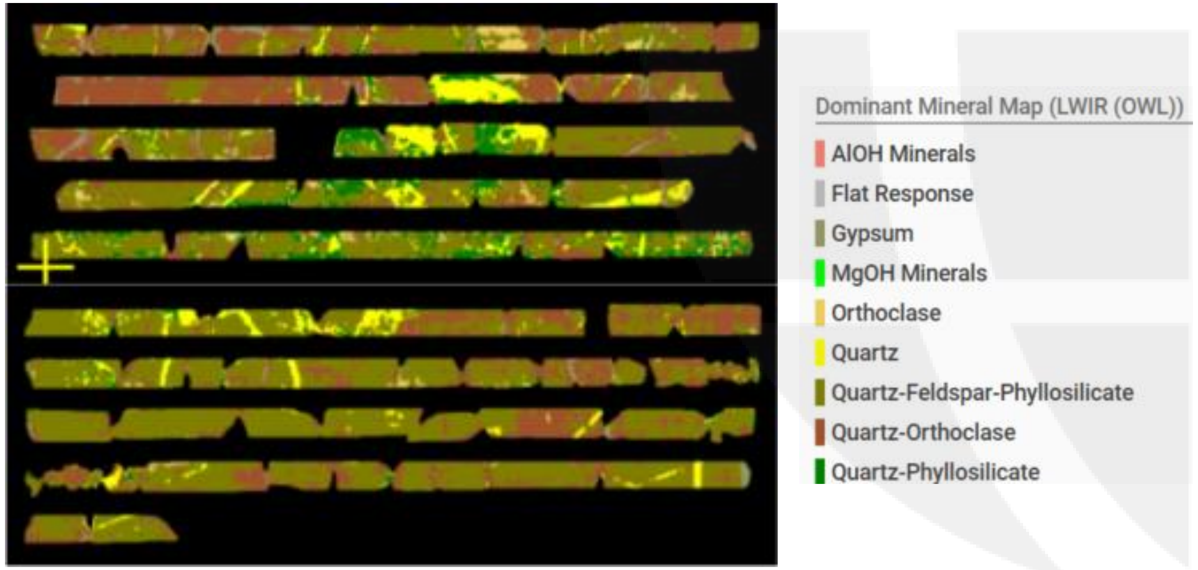
- LWIR responses show abundant and pervasive orthoclase. This is the K-feldspar species present, and the one we most frequently identify spectrally in porphyry systems

- The SWIR shows overprinting whitemica alteration, predominantly muscovite though with some slightly lower temperature illite (potentially an even later overprint?). The quartz veins in the LWIR image are interpreted to be part of the mica alteration

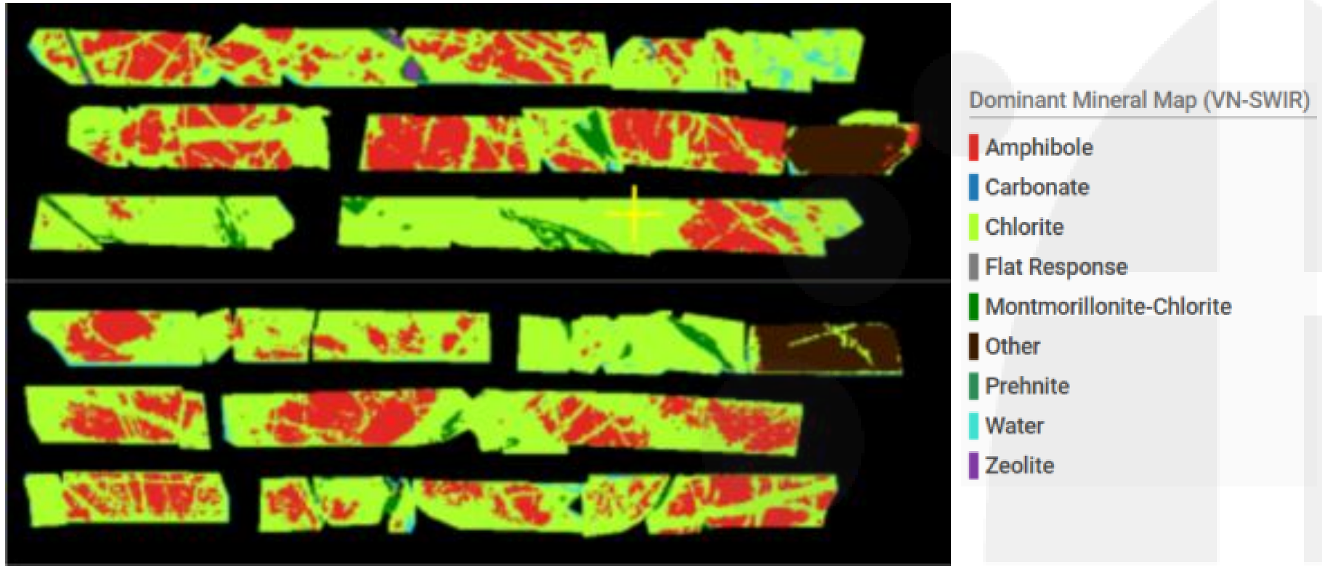
- The SWIR image is slightly misleading as it only captures the overprinting alteration (mica being SWIR active) and not the underlying K-feldspar alteration detected by the LWIR. This shows the power of a combined sensor system

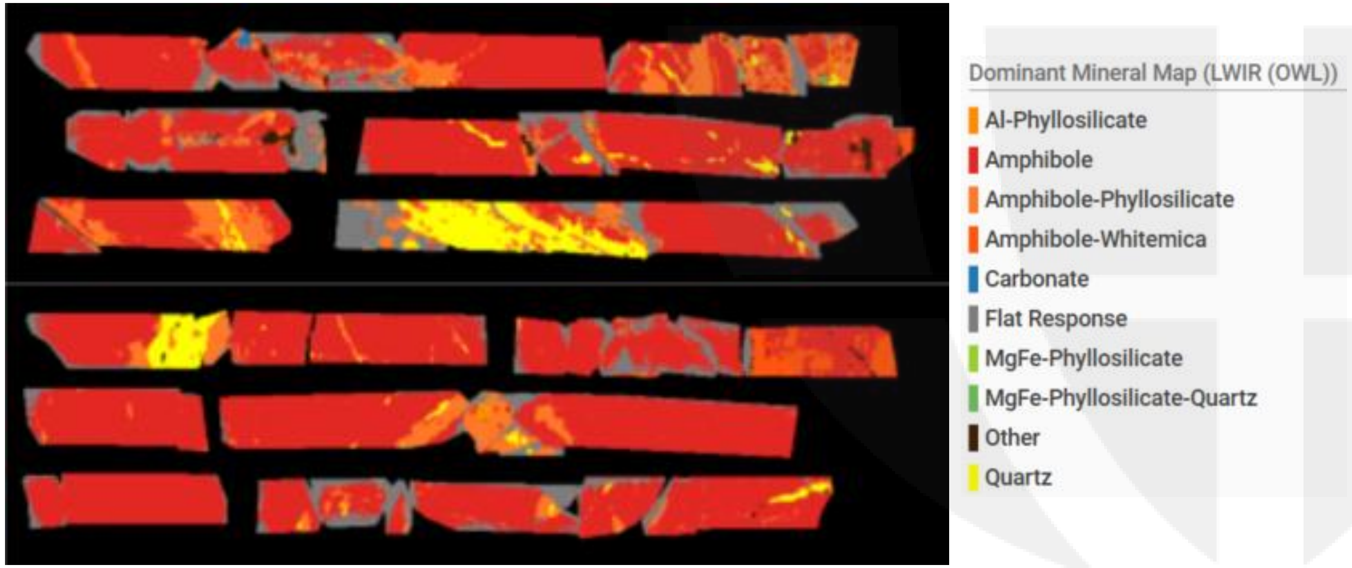
Potassic Alteration





- The example on the left shows another section through potassic alteration
- LWIR responses show abundant orthoclase both as a single phase and with quartz.
- The SWIR again shows overprinting whitemica alteration, the quartz veins in the SWIR may be a component of a quartz-sericite overprint
- Both sensors map abundant gypsum, which is after primary anhydrite. Spectrally, we identify gypsum much more frequently than anhydrite, presumably due to hydration during overprinting later alteration events





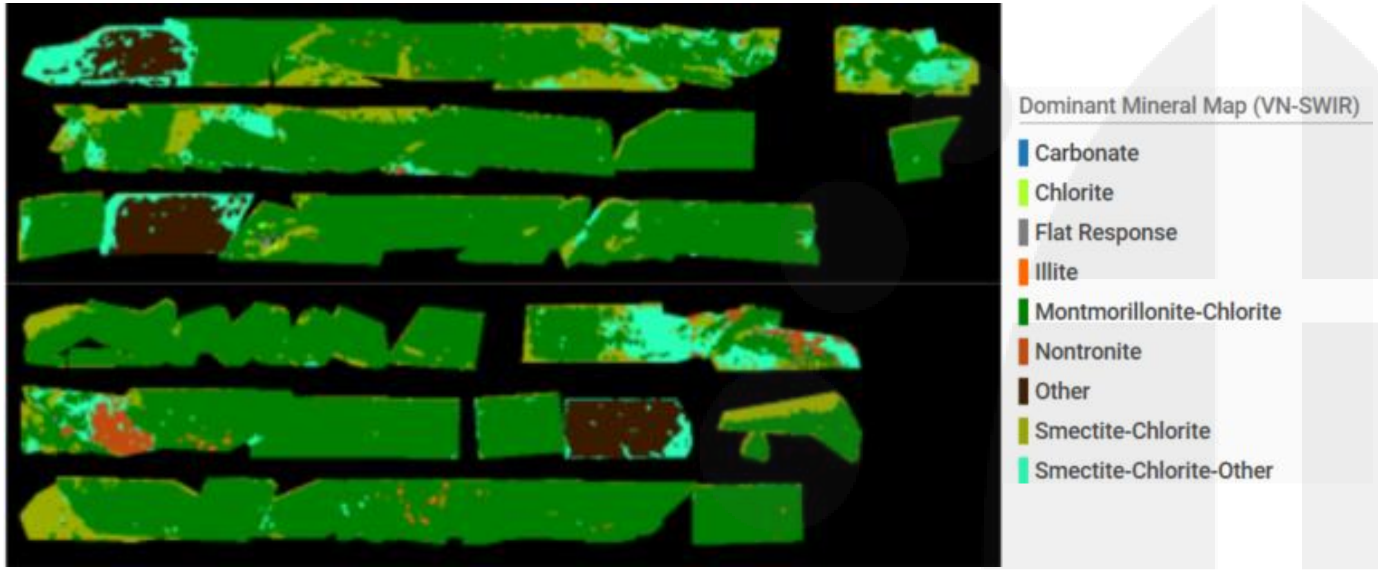
- The mineral maps on the left show an example of propylitic alteration

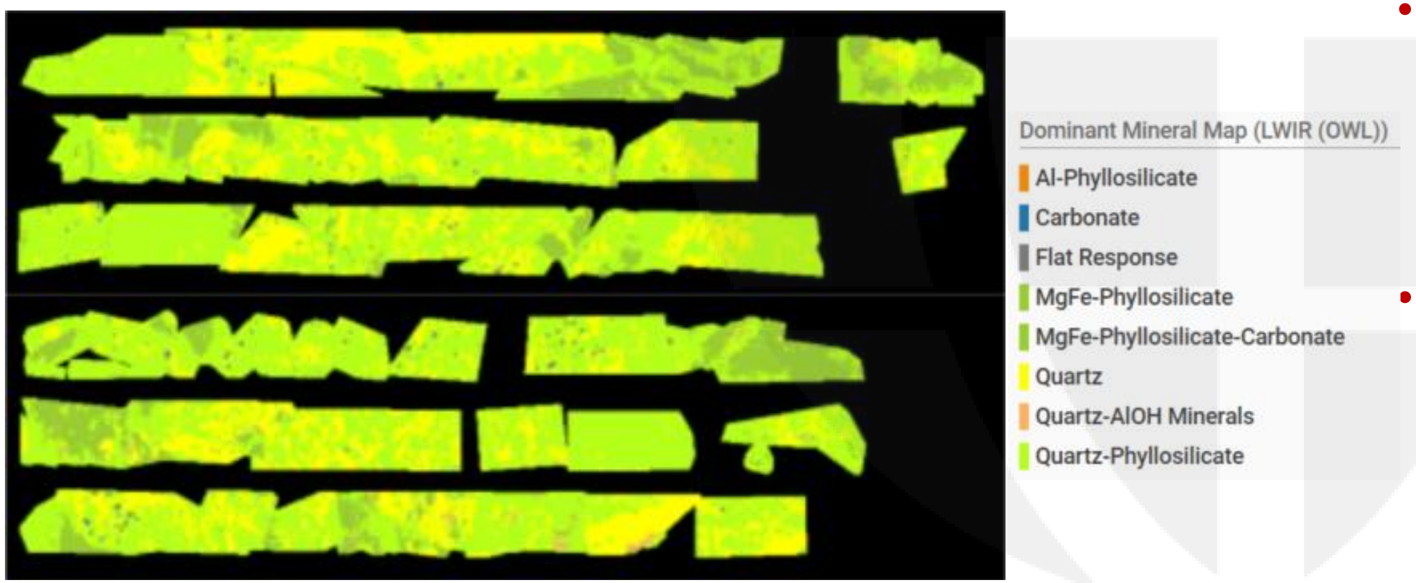
- In this case, the LWIR is predominantly detecting amphibole. Amphibole is also mapped in the SWIR, but to a lesser extent and presumable alteration of amphibole to chlorite and montmorillonite-chlorite is mostly mapped

- The amphibole in this case is actinolite

Propylitic Alteration

Propylitic Alteration





- Another example of propylitic alteration. In this instance no amphibole is present, with chlorite being the dominant phase

- The low temperature nature of the alteration is evident from the presence of montmorillonite (Al-smectite) in an assemblage with chlorite

- Phyllosilicates can be hard to speciate in the LWIR, and in this instance modification of the chlorite response by smectite has led to adoption of the term Mg-phyllosilicate as a descriptor

- The “other” in the SWIR are parts of the core that have been coated in resin, and which strongly affect the SWIR response masking any mineral signatures

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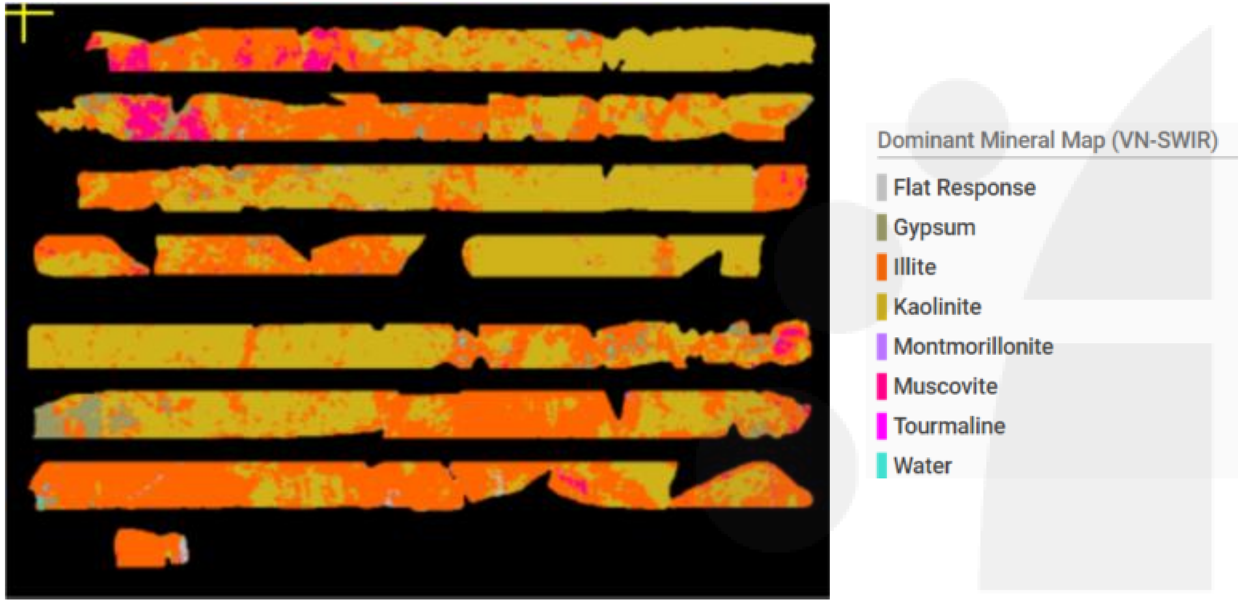
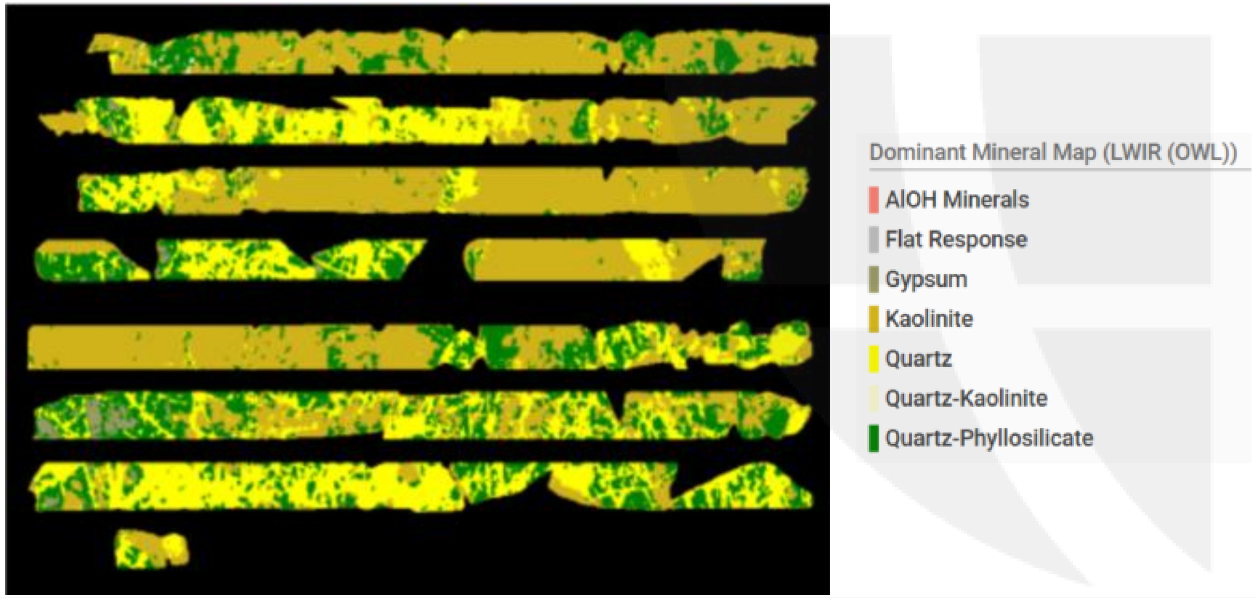
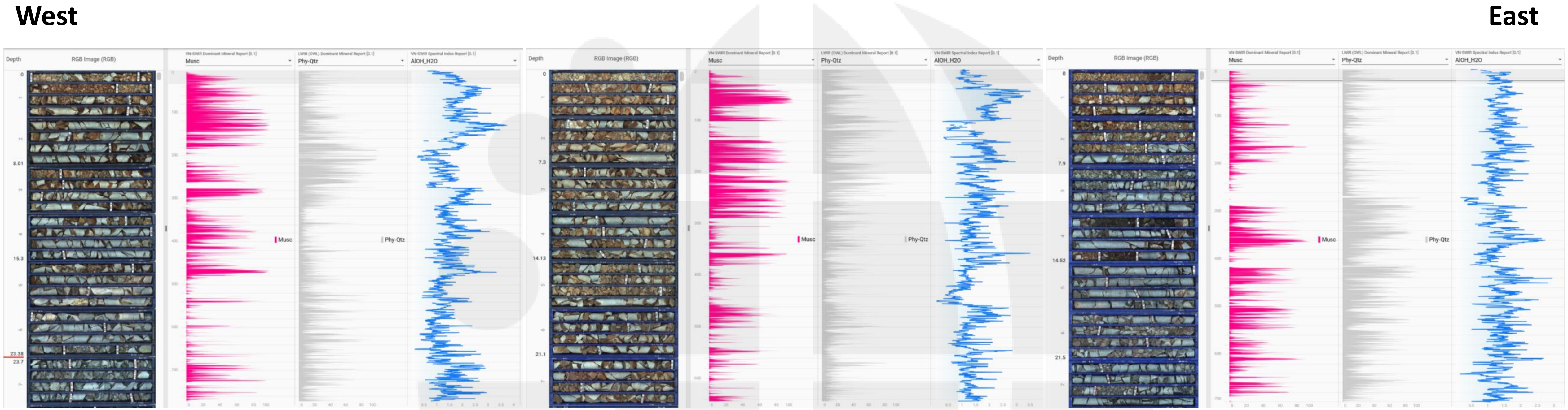




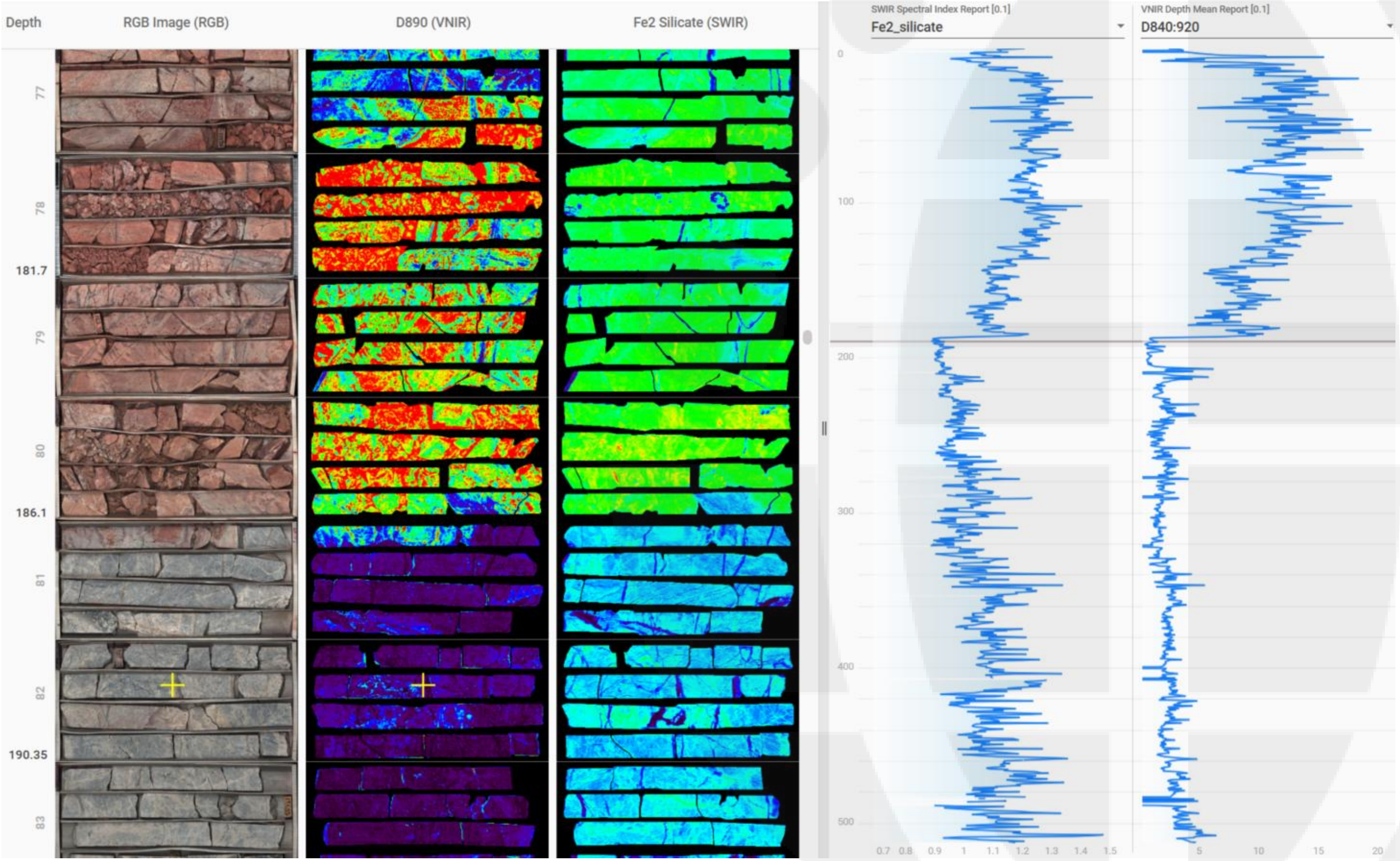
- The images on the left show an example of late argillic alteration
- Only minor muscovite from earlier quartz-sericite alteration is preserved, it has mostly been altered to lower temperature illite
- Kaolinite is well developed as part of the argillic assemblage, suggesting acid conditions
- In the LWIR, quartz occurs mostly with illite and so is interpreted to be part of the quartz-sericite assemblage; it has not been altered during the argillic overprint
- Kaolinite is also mapped in the LWIR, and mirrors that mapped in the SWIR

Argillic Alteration



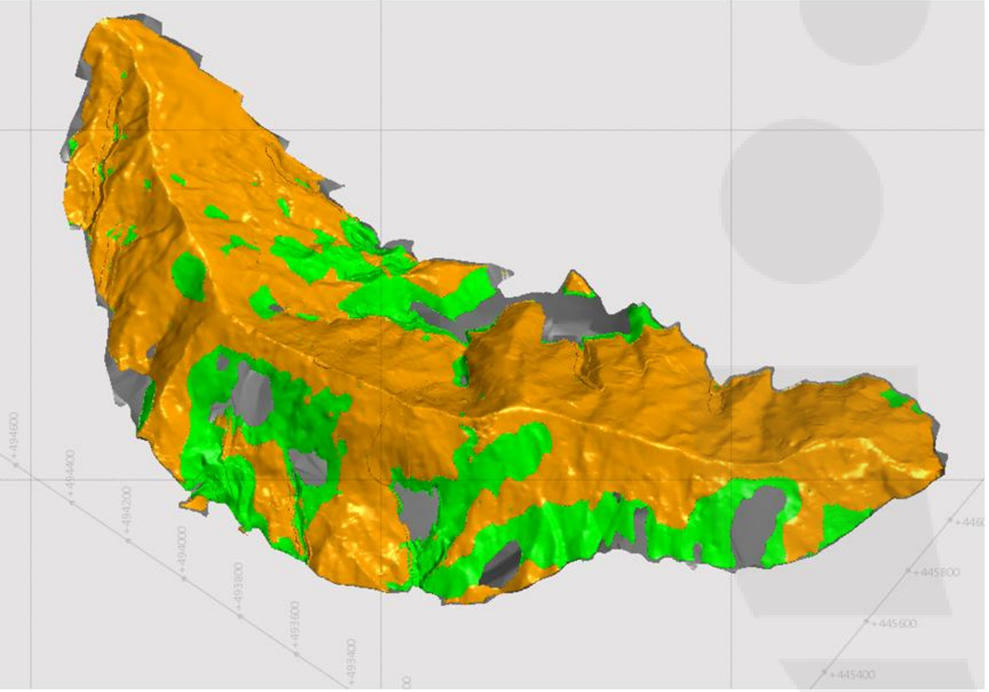
- Above are results for three holes drilled on section into a porphyry target
- While none have definitively intersected the porphyry, muscovitic alteration provides some clues (using phyllosilicate-quartz in the LWIR)
- The hole furthest to the west has the greatest degree of muscovitic alteration, and using the ratio of the Al-OH absorption to bound water as a crystallinity guide it is evident that muscovite in this hole is also more crystalline. The hole furthest to the east has the least crystalline muscovite, and also overall weaker whitemica alteration
- It is therefore clear that future drilling should be directed westwards

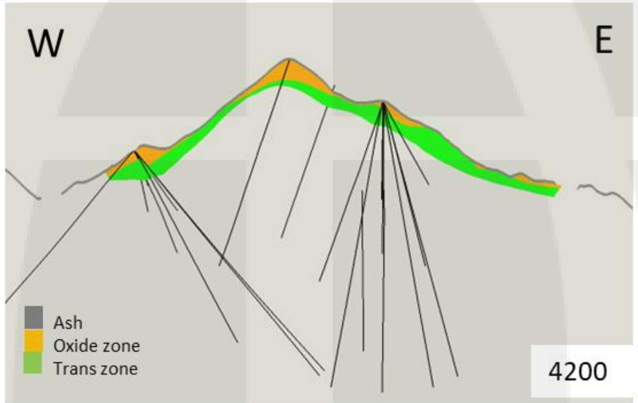
Vectoring

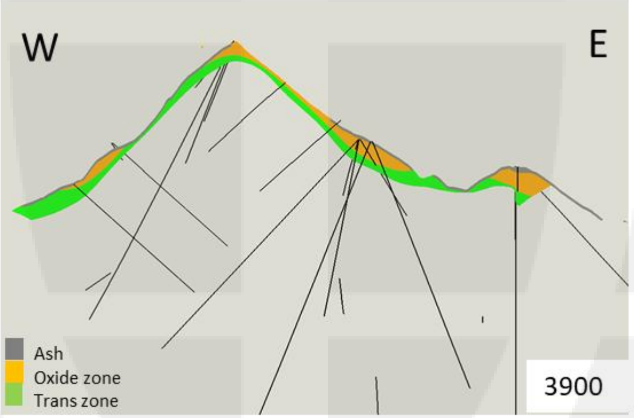


- Accurately defining oxide vs hypogene ore is of importance for both resource estimation and geometallurgy
- The example on the left shows mapping of iron oxides using both the VNIR and SWIR
- The base of oxidation is very well defined at ~180 metres depth

Mapping Oxidation



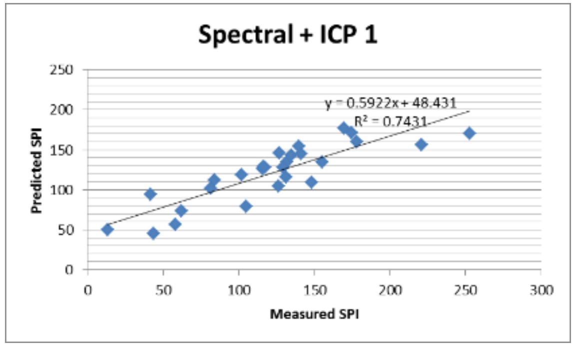




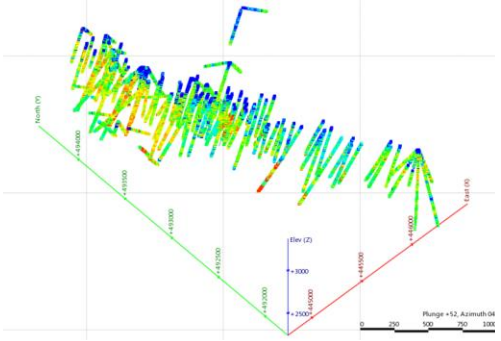
- With sufficient data, 3-D maps can be created of oxide vs hypogene
- Spectral data are also very useful for defining the hard to identify transition zone, that partially oxidised area between oxide and hypogene ore
- The transition zone is critical to map because recovery is generally poor no matter the concentration method, and forewarning is important
- Minerals such as nontronite, jarosite and alunite are often indicative of transition material

Mapping Oxidation

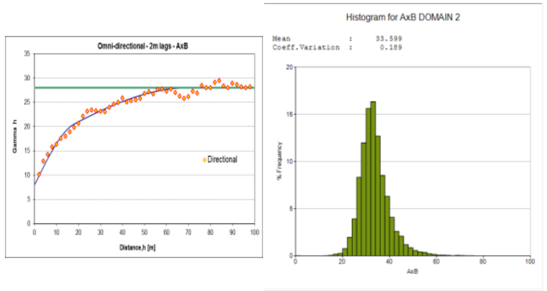
Geometallurgical Mapping – Porphyry Example



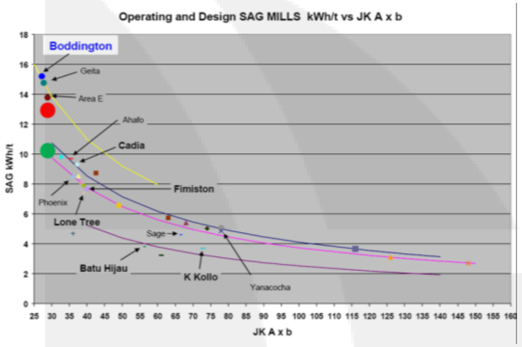
Step 1: correlation of hyperspectral + geochemistry with metallurgical parameters



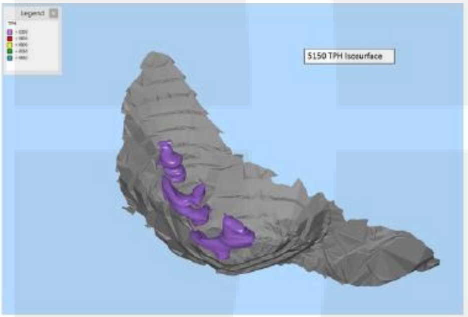
Step 2: 3-D modelling of predicted values for QA/QC



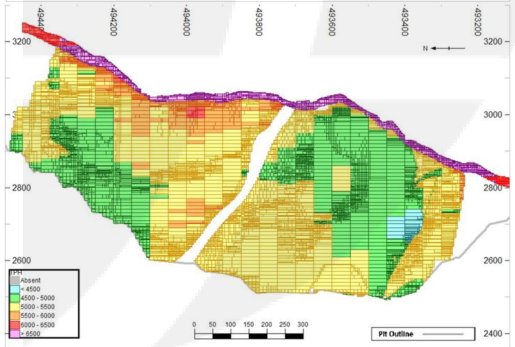
Step 3: estimation of predicted parameters into block model via ordinary kriging



Step 4: transformation to throughput using plant design and published performance of similar plants



Step 5: creation of 3-D wireframes of throughput cutoffs



Step 6: detailed study to identify geological drivers of throughput, assessment of PFS assumptions and viability

Conclusions

- Hyperspectral core imaging provides excellent data for porphyry exploration and geometallurgical assessment
- The different alteration assemblages have distinctive mineralogical signatures that are spectrally responsive
- The LWIR adds an additional dimension to mapping, and often allows mapping of early alteration that has been overprinted – the SWIR generally maps the overprint only
- Definition of oxide vs hypogene, and importantly also transition zone material, can be confidently and consistently mapped
- Geometallurgy is of real importance for large tonnage and low-grade deposits such as porphyries where economics can be readily affected by material type