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Hyperspectral Core Imaging for Skarn Deposits

Introduction

- Skarn is the term used for alteration caused by contact metamorphism and metasomatism related to intrusives, or less commonly by regional metamorphism
- Skarn is defined by mineralogy, which generally involves a range of calc-silicate minerals
- Alteration occurs on both the prograde path (high temperature minerals) and the retrograde path (generally hydrous minerals), with the relative proportions of these two types largely controlled by the depth of skarn formation
- An important distinction is between skarn, and skarn deposits which are economically mineralized. Skarn deposits are significant hosts and producers of Cu, Au, Fe, W, Mo, Sn and Zn
- Skarn deposits are related to alteration and mineralization caused by (generally felsic) intrusives, exoskarn refers to alteration of sediments in the country rock (most commonly carbonate) and endoskarn to alteration of the intrusive itself and any pre-existing igneous rocks
- Skarn deposits can be related to any of I, S or A type granites and so form in diverse tectonic settings

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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

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- Possibly more than any other deposit type, skarns require the long-wave infrared (LWIR) to properly map mineralogy. Many calcsilicate minerals do not have diagnostic short-wave infrared (SWIR) responses, and use of this range alone is severely limited; especially for garnets and clinopyroxenes that are key to mineral mapping. Slides 6 and 7 show examples of this, and how a misleading interpretation could easily be made in the absence of the LWIR

- However, minerals formed on the retrograde path are generally hydrous and so can be detected using the SWIR

- Carbonates, epidote and vesuvianite are all responsive in both wavelength ranges, although may be better defined in one range depending on the mineral assemblage

- We are fortunate that skarn minerals may show subtle but detectable changes in spectral response related to chemical composition, which is critical for vectoring and unravelling complex alteration histories. This is true especially for garnet, carbonate and epidote and to lesser extent (as currently known) for clinopyroxenes

- The following slide shows VN-SWIR and LWIR library (USGS and JHU) spectra for a range of common minerals, in addition to these we have also identified and mapped other skarn phases such as wollastonite and monticellite

Hyperspectral Responses of Skarn Minerals

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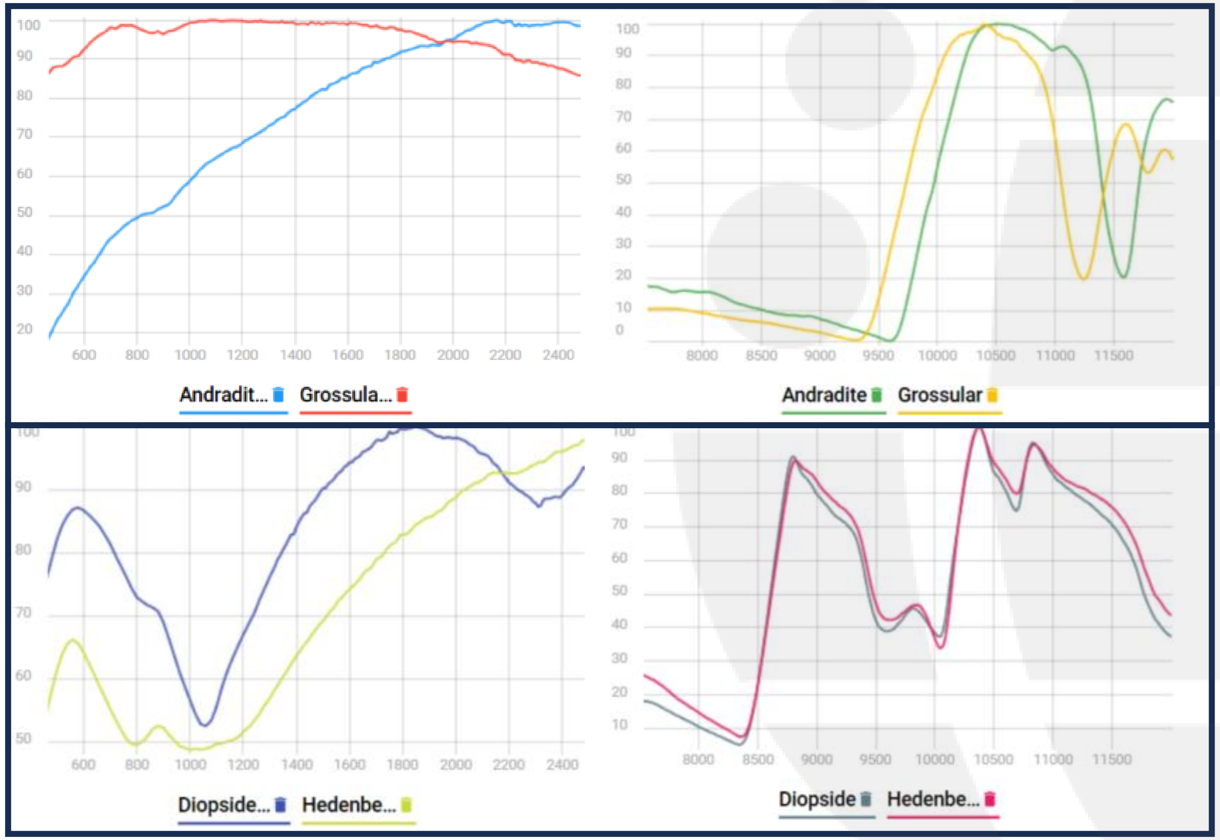
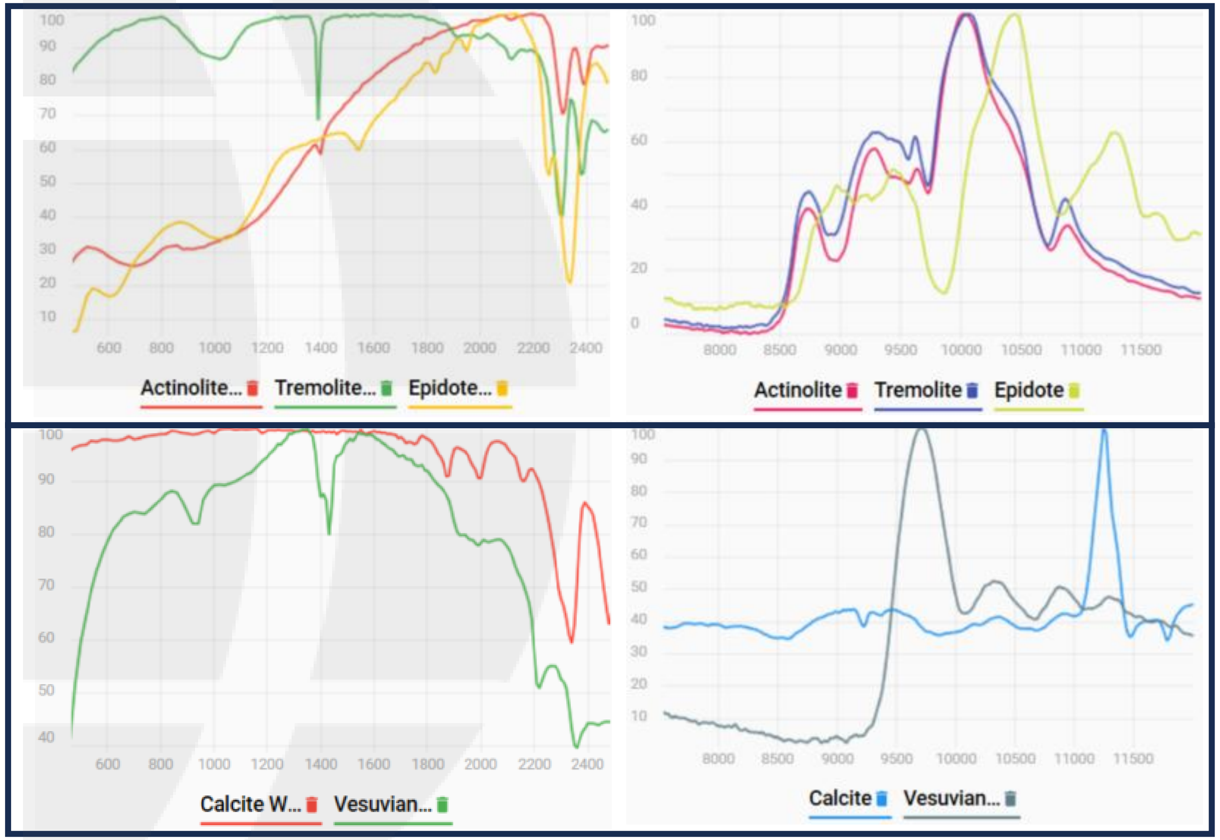
VN-SWIR **LWIR**



VN-SWIR **LWIR**



Hyperspectral Responses of Typical Skarn Minerals

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- The images on the left are colour (RGB) at the top, SWIR mineral map in the centre, and LWIR mineral map at the bottom
- SWIR mapping is dominated by vesuvianite shown in green, suggesting a strong retrograde overprint by this mineral
- However, the LWIR map at the bottom is dominated by grossular garnet (pink) with lesser vesuvianite (green) indicating that retrograde alteration only partially overprints
- This example shows how mineral mapping is affected by the strength of mineral responses in different wavelength ranges, and that comprehensive mapping via integration of the LWIR with the SWIR is essential

Skarn Mineral Responses SWIR – LWIR

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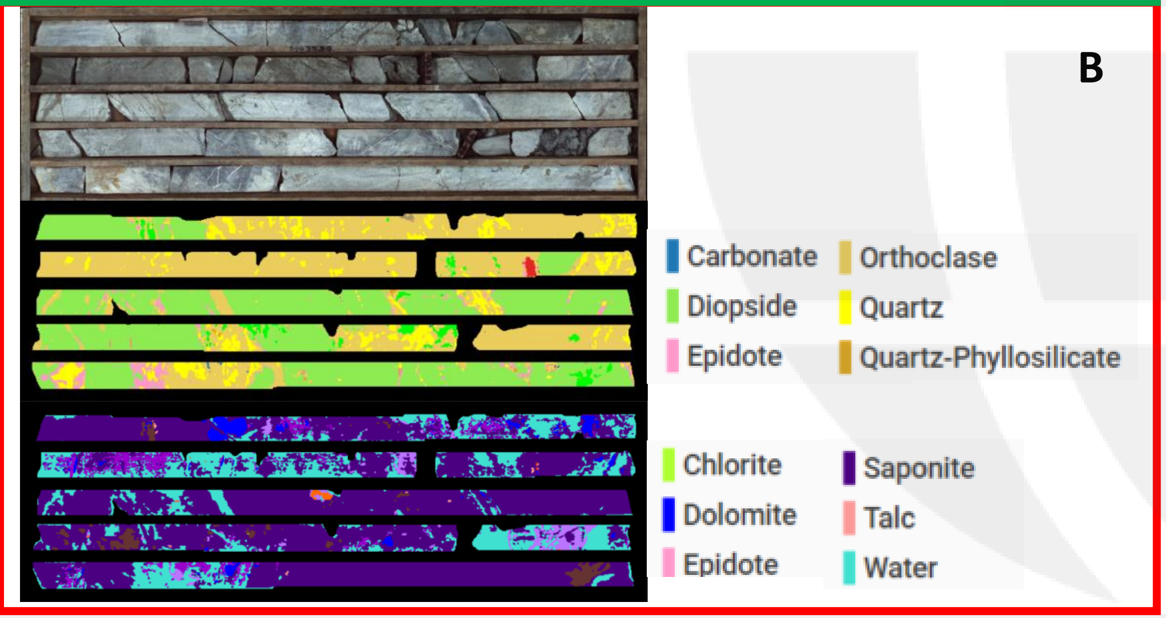

- The images in the boxes labelled A and B are true colour (RGB) at the top, LWIR mineral map in the centre, and SWIR mineral map at the bottom
- In the top box (A), strong andradite skarn is developed with cross-cutting quartz veins. The SWIR mapping picks out unbound water (~1950nm, broad feature) consistent with fluid inclusions in the garnet
- In the lower box (B), the LWIR maps diopside skarn with adjacent quartz-orthoclase (potassic) alteration. In this instance, the SWIR is detecting saponite (an Mg-rich smectite) as the main phase. The presence of saponite could be interpreted as a form of retrograde alteration, however its absence from the LWIR map rather suggests that this represents a very weak deuteric effect. Since saponite is the only mineral present that is responsive in the SWIR, its importance and strength is overstated. Both ranges together are essential for geological interpretation

Skarn Mineral Responses SWIR – LWIR

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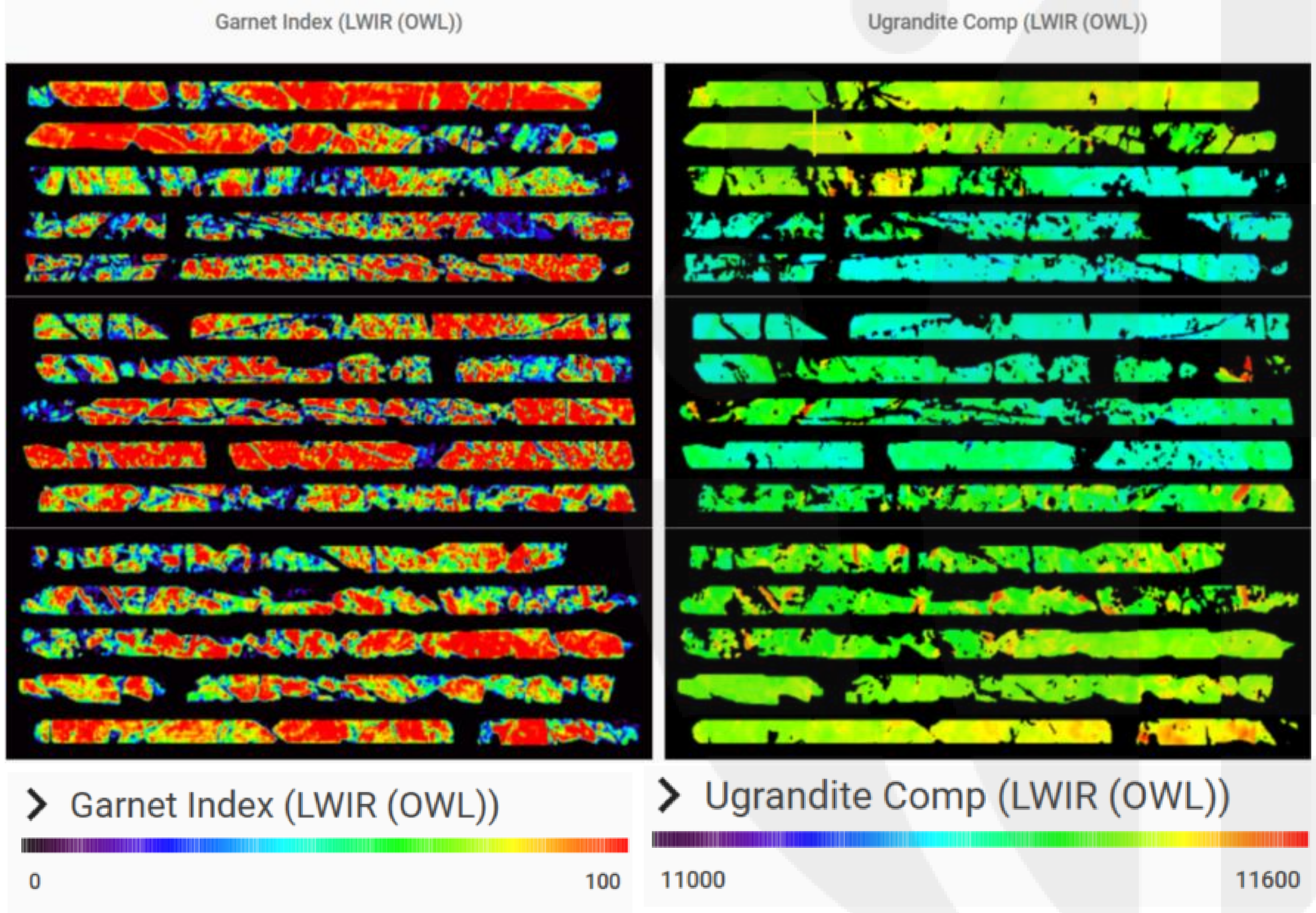
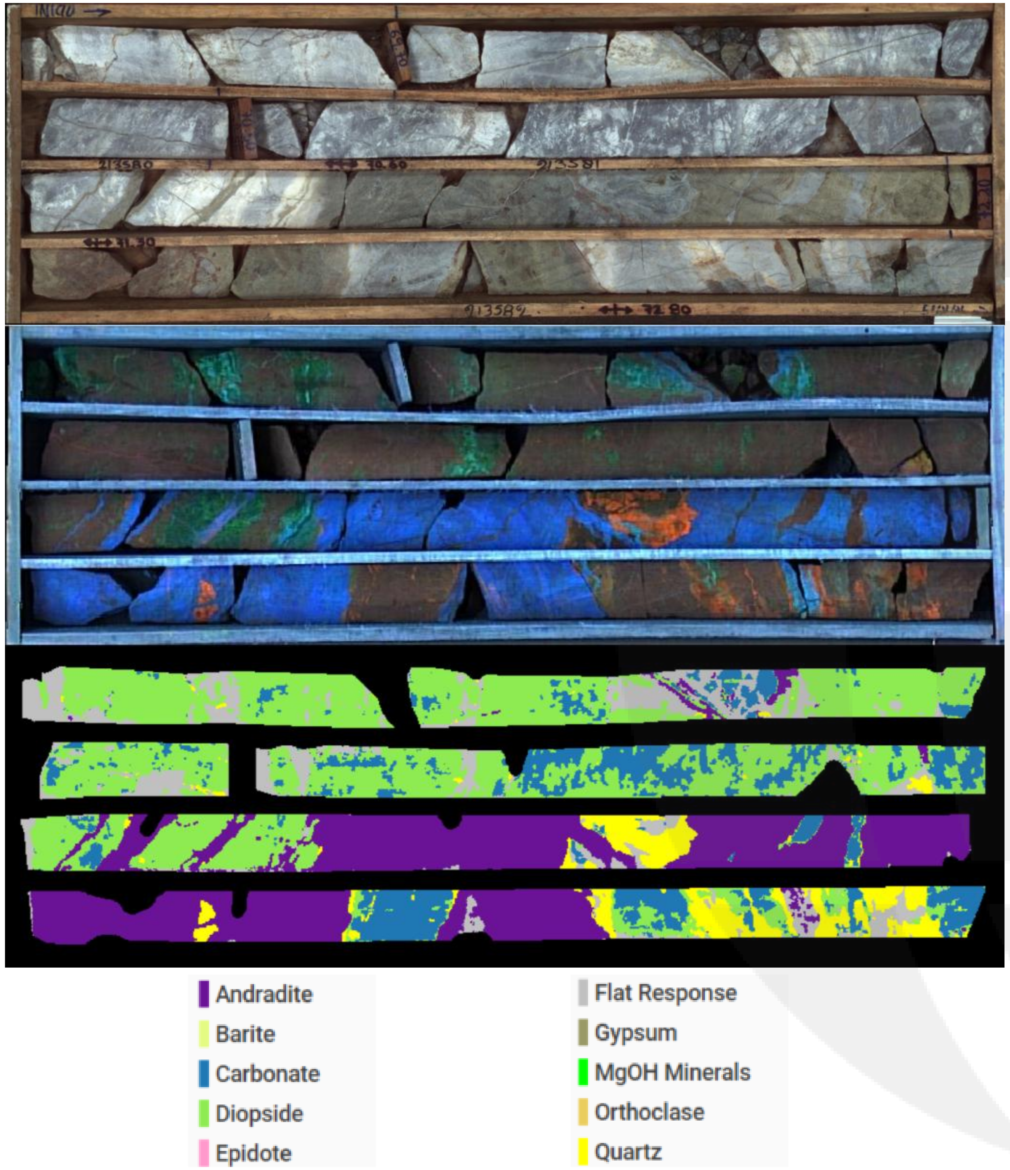


- The images show garnet intensity as calculated by the scaled magnitude of the ~11400nm trough, and composition which is related to the wavelength position of the trough
- Garnet alteration in this example is generally intense, and compositionally displays a wide range of variability from close to 11200nm (Ca-rich grossular) to almost endmember Fe-rich andradite near 11600nm
- Garnet chemistry is a key vector in skarn deposits

Garnet Intensity and Mineral Chemistry



- The images on the left are true colour (RGB) at the top, LWIR false colour composite image in the centre (FCC), and a LWIR mineral map at the bottom
- Note the variety of mineral textures on the map, with incomplete alteration of carbonate leaving blebby patches, while garnet skarn is focused into discrete zones of 30-300 mm width. There are potentially two generations of diopside present, one pervasive (perhaps early?) and the second as a halo to garnet alteration
- On the FCC, note how the garnet-rich areas show up as bright blue, while diopside skarn is brown and green. This product can be generated almost instantly during data capture, and so is a great aid to logging

Texture and Paragenesis

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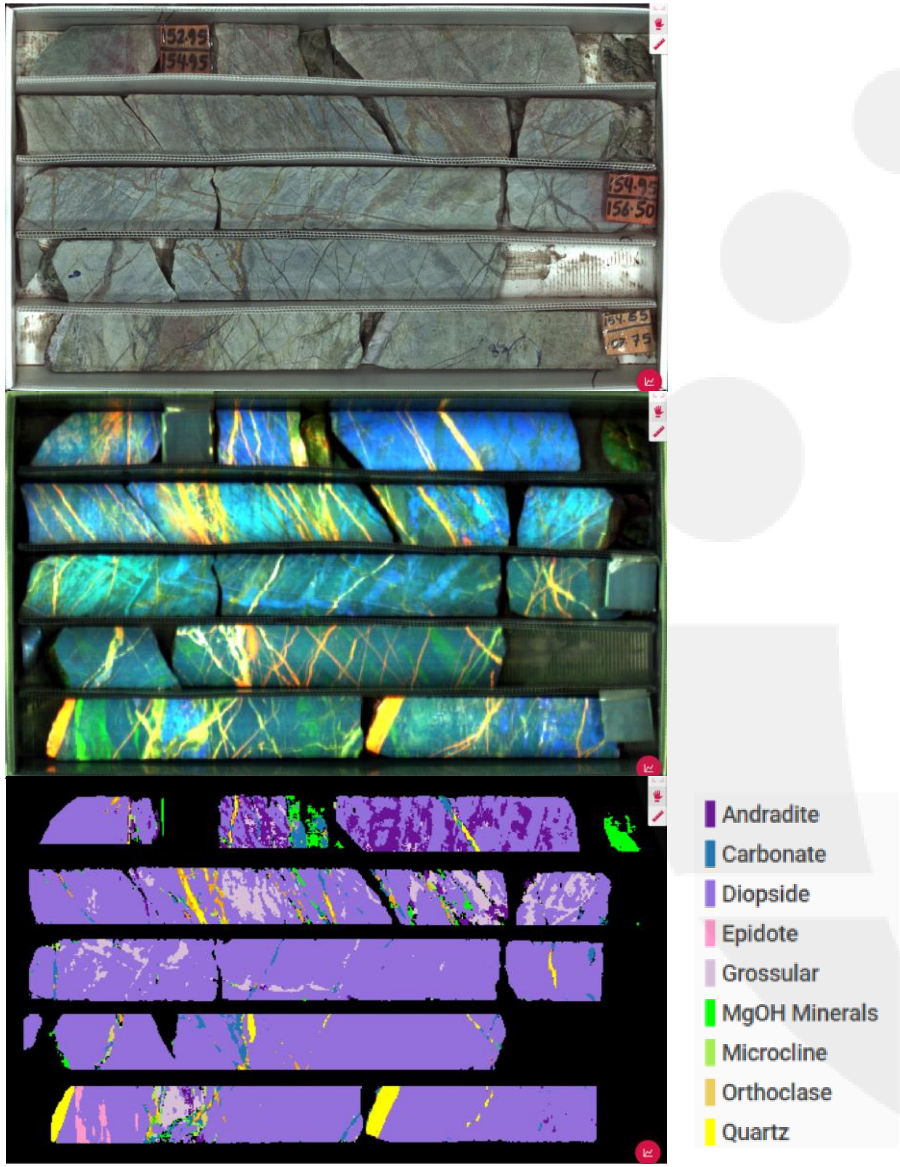
Texture



- The images on the left are true colour (RGB) at the top, LWIR false colour composite image in the centre (FCC), and a LWIR mineral map at the bottom
- This example shows some spectacular texture, including complex diopside-grossular-andradite skarn and late quartz veins
- The mineral map does a decent job of capturing texture, but being a binary (yes/no) product is not always as effective as the FCC
- The one texture definitely shown better by the mineral mapping are the blebby zones of andradite and grossular skarn within the broader diopside envelope

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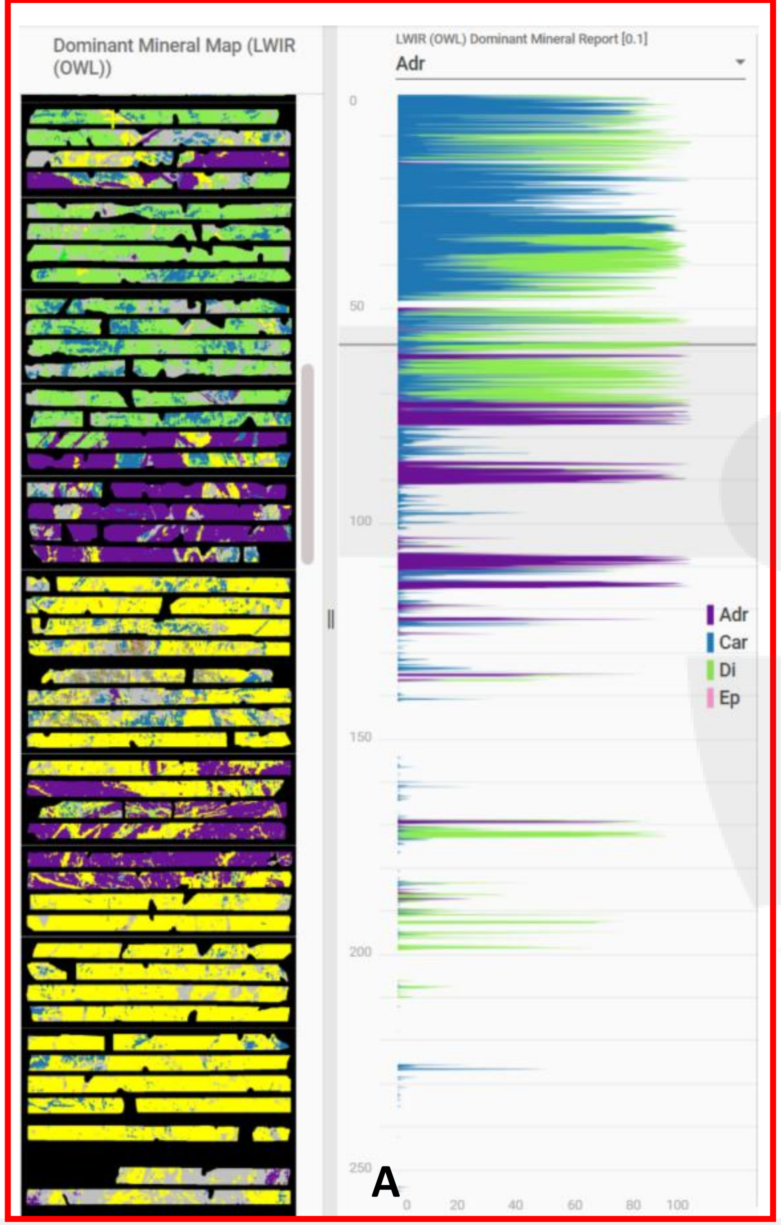

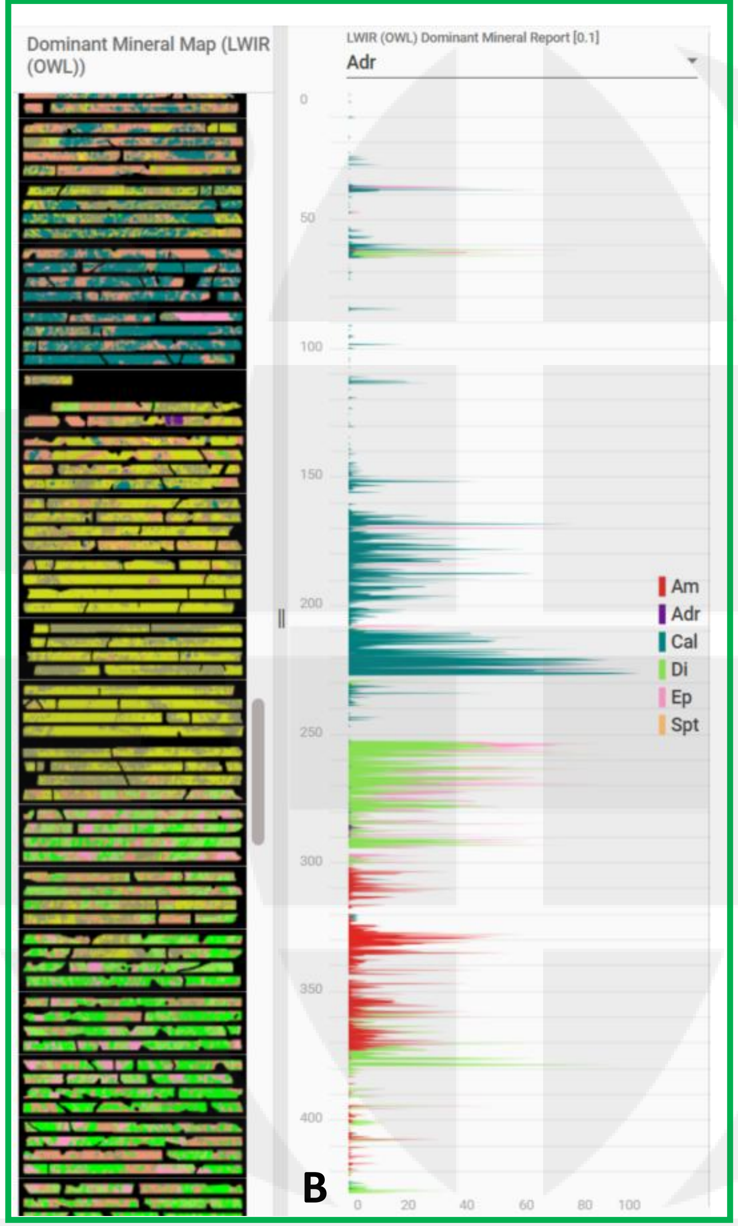

- The mineral map and profile on the left (marked A) is proximal garnet-diopside skarn (garnet is andraditic) associated with Cu mineralization
- The mineral map and profile on the right (marked B) is from a more distal part of the same system which is richer in Zn and Pb, with diopside-epidote skarn, preserved carbonate, and a zone of retrograde amphibole and serpentine

Distal vs proximal skarn

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- The following slide shows mineral mapping of three boreholes from a single skarn deposit
- The maps and profiles on the far left (Hole A) are from the causative intrusion and show typical quartz-feldspar-Al phyllosilicate (predominantly mica) alteration. Skarn alteration is weak to absent
- The maps and profiles in the centre (Hole B) are from well developed garnet-diopside skarn, but which is restricted to a ~30m wide zone from 250 metres depth along with a broader zone of weak retrograde alteration just below that (amphibole and Mg-Fe phyllosilicates). This skarn occurs virtually at the contact of the quartz-feldspar-mica altered intrusive, with the retrograde skarn occurring distally relative to the prograde garnet-diopside skarn
- The maps and profiles on the right (Hole C) are from a strongly developed and zoned garnet-diopside skarn of ~100 metres thickness, with no evidence for retrograde alteration. Variation in garnet chemistry from grossular to andradite is recorded, with the bulk of the garnet being andraditic. The skarn is developed along the intrusive contact, with a small amount of intrusive intersected at the very bottom of the hole. Diopside skarn can be seen to be distal to garnet skarn with respect to the intrusive

Retrograde skarn

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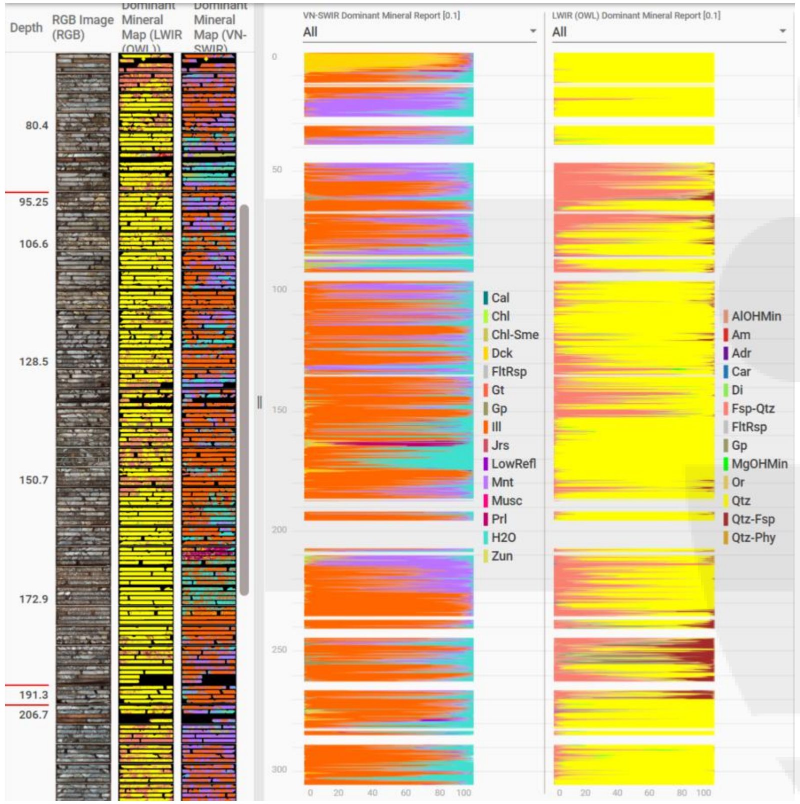
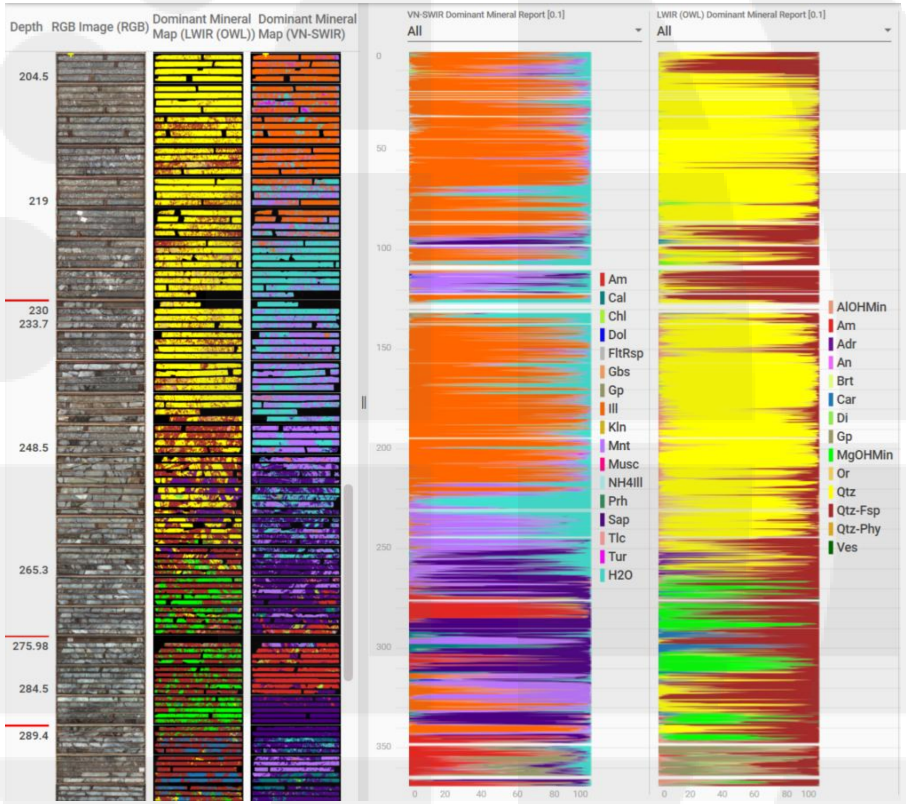
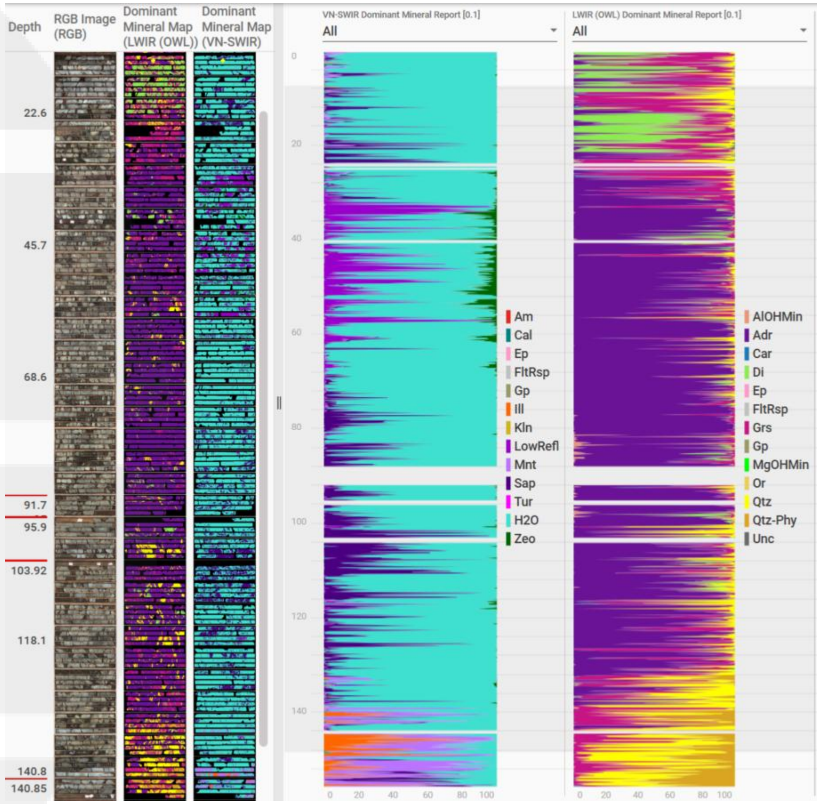
HOLE A



HOLE B



HOLE C



Skarn Intensity

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Conclusions

- Hyperspectral core imaging is a powerful tool for unravelling and modeling alteration associated with skarn deposits, and in this case, addition of the LWIR is essential to ensure robust geological interpretation

- Imaging provides two major benefits over point spectrometers, the ability to look at textural expressions and paragenesis, and the fact that alteration mapping is continuous and so completely representative

- Mineralogy is critical for modelling skarn alteration, the ability of the technology to identify and map compositional changes of minerals such as garnet adds a valuable extra dimension