TERRACORE

GEOSPECTRAL IMAGING

Hyperspectral Core Imaging for Epithermal Precious Metal Deposits

- The term epithermal refers to the formation of precious metal (Au-Ag) mineralization at low temperatures, typically 150-300°C and at shallow crustal levels. Most known deposits are young, given that their shallow depth of formation doesn’t typically lead to good preservation

- This term is applied to three distinct types of mineralization, that vary predominantly in the nature of their fluid (both origin and chemistry), orebody morphology, and associated alteration

- The three types are named high, intermediate and low sulphidation with that distinction based on the amount of sulphur in the fluid and so the amount of sulphide deposited during mineralization and alteration

- Alteration mineralogy is of special importance during early stages of exploration to determine the nature of any possible mineralization, and so the expected morphology of that mineralization. That knowledge is essential to properly guide drill programs

- As alteration is generally very fine-grained, and so difficult to accurately determine by eye, the use of spectral methods is of significant value

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 epithermal systems, mainly VN-SWIR using handheld (point) instruments. Of course, the use of imaging retrieves the textural context of alteration minerals
- Given the generally fine-grained nature of alteration, the addition of spectroscopy adds enormously to understanding of alteration systematics
- Most of the common alteration minerals, such as white mica (generally illitic), kandite clays, alunite, jarosite, smectite clay, kaolinite, chlorite, carbonate, and the ammonium minerals are active in the SWIR. Propylitic minerals such as chlorite, epidote and amphibole are also SWIR active
- The LWIR adds adularia when present, and can also be used to investigate quartz textures which may provide important information; it is also very sensitive to carbonate
- Information about mineral composition and crystallinity can be of key importance for vectoring

Hyperspectral Responses within Epithermal Systems

Low Sulphidation Introduction

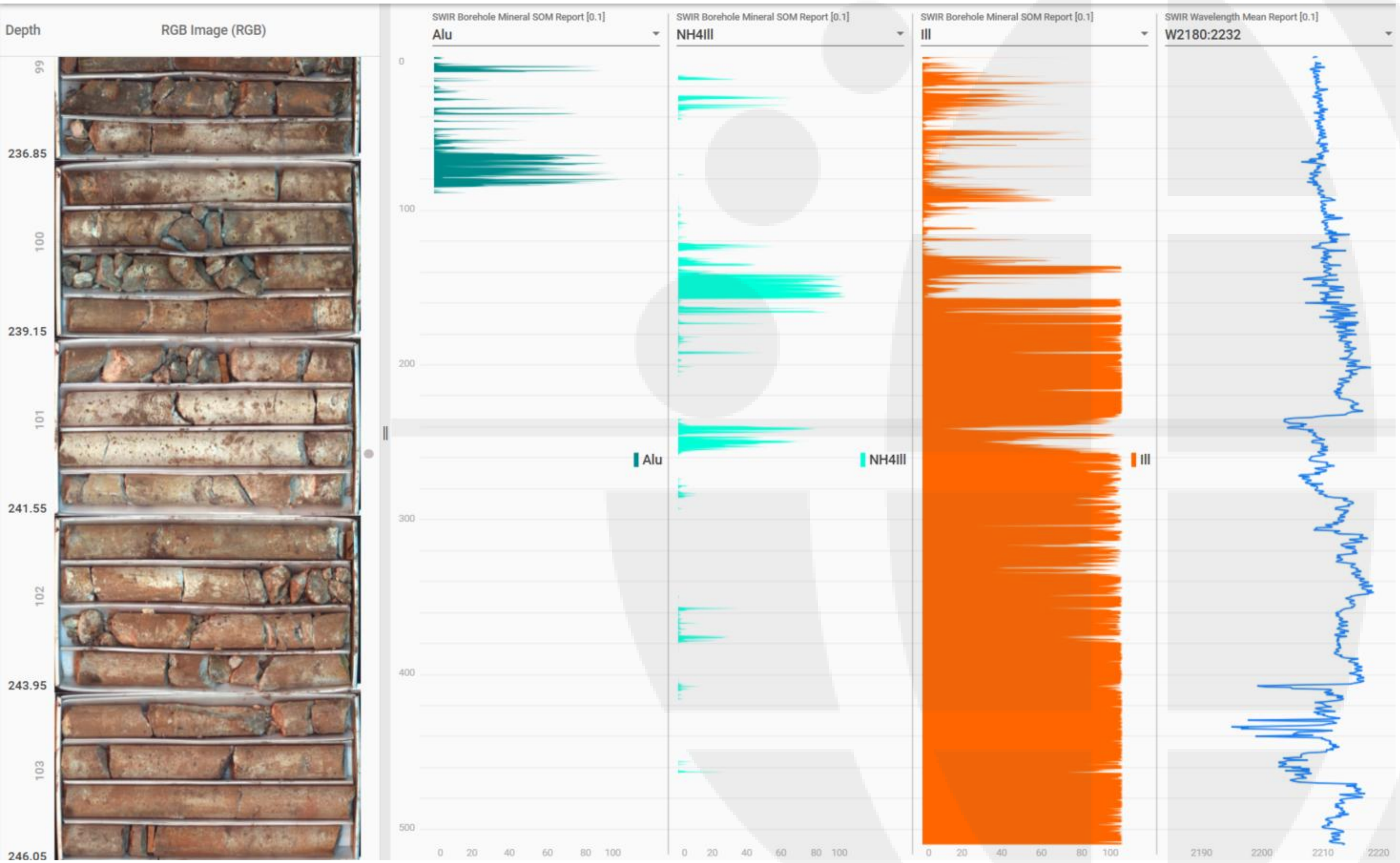
- Low sulphidation Au-Ag deposits are a significant source of production for precious metals. They are often very high grade (so called bonanza zones), metallurgically simple, and so present an attractive exploration target

- While there are certainly variations in low sulphidation epithermal deposits, especially in their geodynamic setting (both arc and rift environments) they all have common characteristics of metal transport and deposition from near-neutral, reduced, low salinity hydrothermal systems dominated by meteoric fluid (magmatic fluid may be a minor component, but magmatism is an important heat source), metal deposition by boiling or mixing at low temperatures, metal deposition predominantly in multistage quartz veins that are typically steeply dipping, low sulphide contents, and significant alteration haloes of generally volcanic rocks (most often felsic volcanics, but andesites can be common)

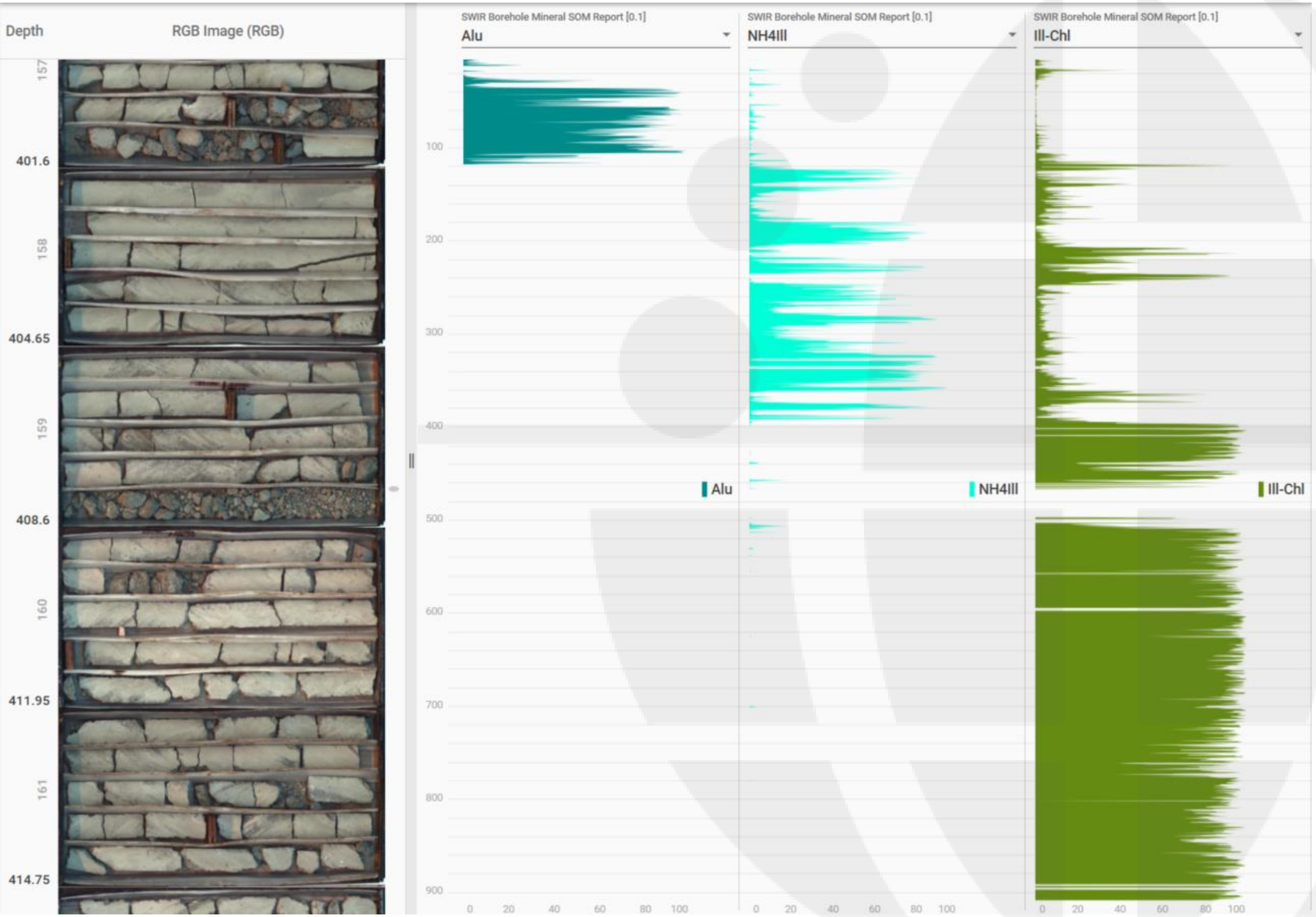
- The surface expression is often a hot spring or geyser, with formation of silica sinter. This passes downwards into a steam-heated lithocap (steam generated from boiling), where highly acidic conditions may exist leading to the formation of quartz-alunite, dickite and kaolinite, while alteration around the veins is predominantly illite grading outwards to illite-smectite and finally propylitic alteration

- Adularia may be an important vein mineral, or occur proximal to veins, and in certain areas such as the Great Basin in the US and the Zacatecas area of Mexico, ammonium minerals are a significant component of the alteration suite. Carbonates may also be important alteration minerals

Alteration Zonation



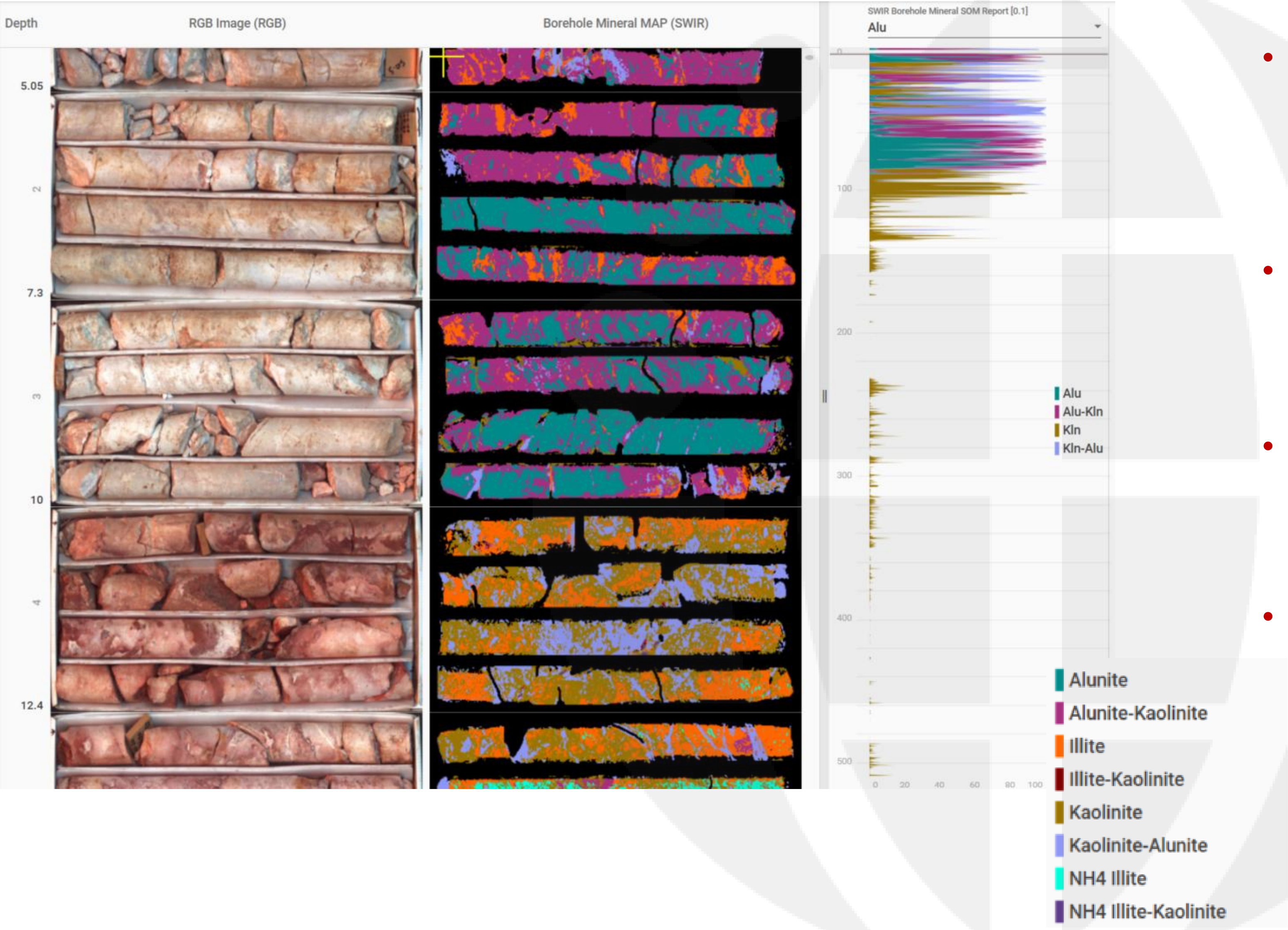
- The plots on the left show selected mineralogy for a mineralized drillhole
- Alunite has been selected as the indicator mineral for the steam-heated zone, hydrogen partitions strongly into the vapour phase during boiling and via acid formation reduces the pH to 2-3
- Below the steam-heated alteration is a zone of ammonium illite + buddingtonite, reflecting transport of NH_3^+ to higher levels of the alteration system (above the boiling zone)
- Illitic alteration is developed from the zone of boiling and deeper, where it occurs as pervasive alteration between veins. Note that illite composition (W2180:2232) is variable, becoming shorter wavelength and so more Al-rich proximal to veins



- The plots on the left show selected mineralogy for a drillhole on the margin of mineralization
- As previously, alunite has been selected as the indicator mineral for the steam-heated zone, hydrogen partitions strongly into the vapour phase during boiling and via acid formation reduces the pH to 2-3
- Below the steam-heated alteration is a zone of ammonium illite + buddingtonite, reflecting transport of NH3 to higher levels of the alteration system (above the boiling zone)
- In this case, as we move distally to the veins, chlorite joins illite as an alteration phase. True propylitic alteration will be illite absent

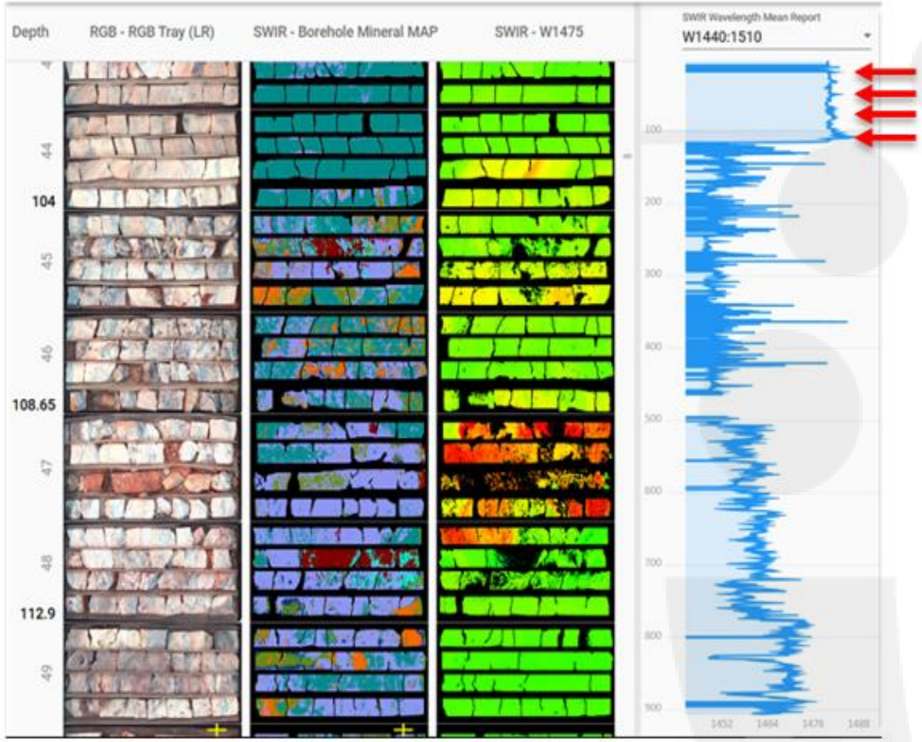
Alteration Zonation

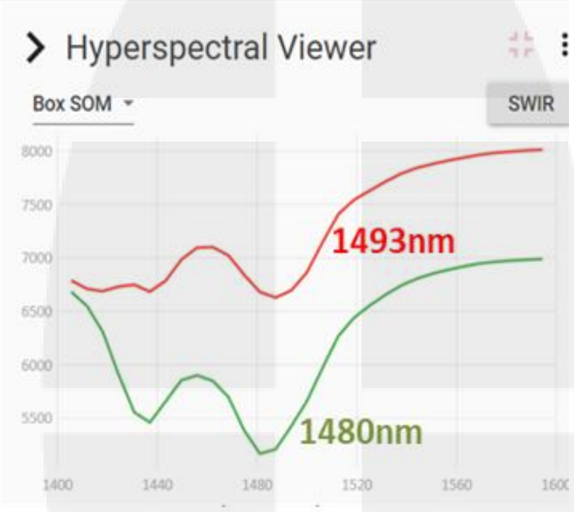
Mineral Chemistry – Unraveling the Lithocap



- The images on the left show a colour image of the core along with the mineral map. This is for a few boxes towards the top of the hole, within the barren steam-heated zone (lithocap)
- A plot of the advanced argillic minerals that constitute the bulk of the lithocap is to the right of the images
- Mineral mapping is somewhat chaotic, with zonation impossible to define except for the extension of kaolinite below the lithocap zone
- Identifying structures is impossible to do, meaning that figuring out where to target below the lithocap is tricky using the data in this fashion

Mineral Chemistry – Unraveling the Lithocap

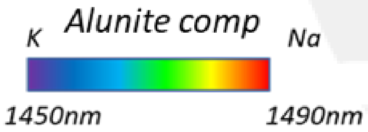




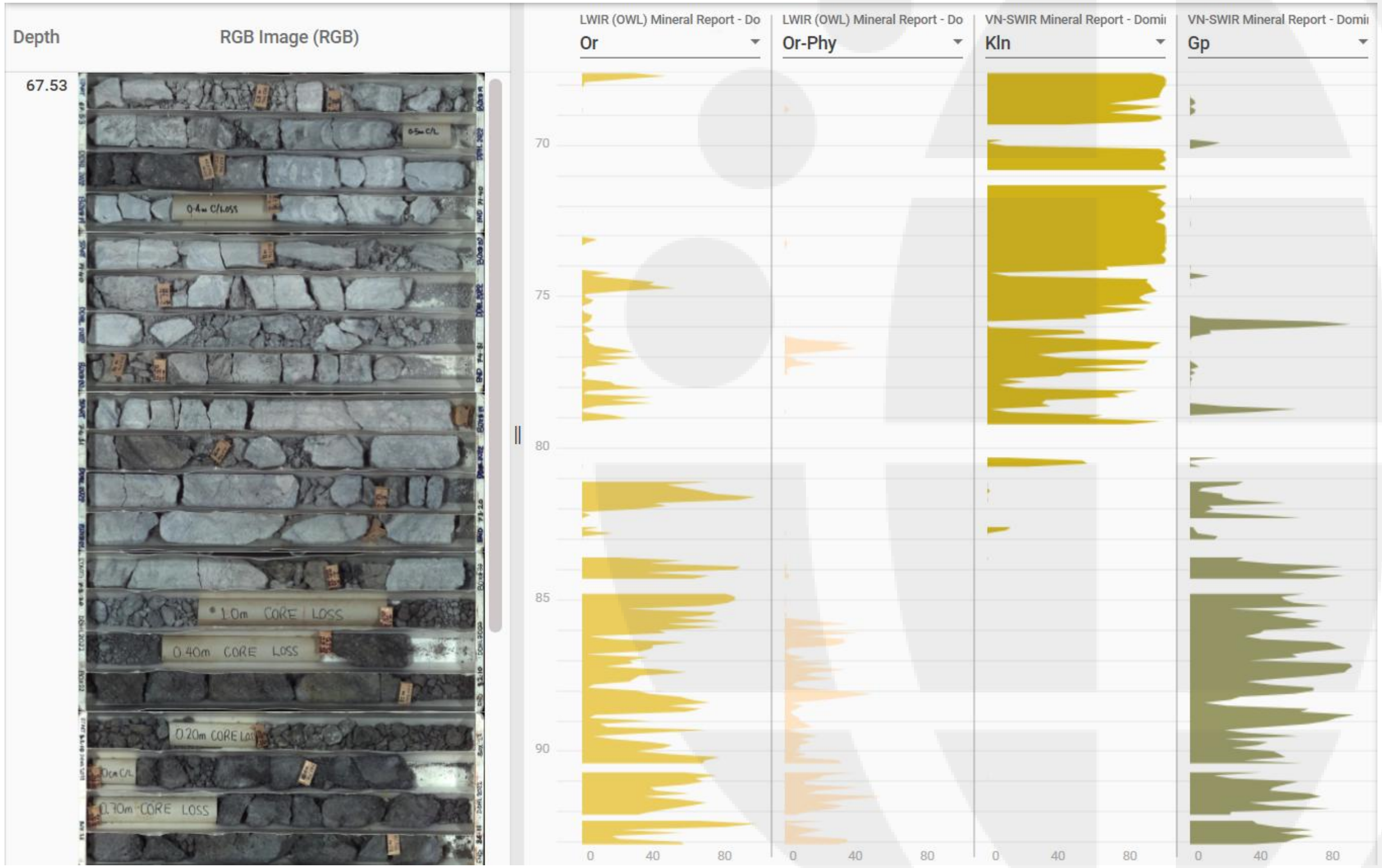
Mineral Legend

SWIR: Borehole Mineral MAP

- 🟩 Alunite
- 🟪 Alunite-Kaolinite
- 🟥 Buddingtonite
- 🟧 Illite
- 🟦 Illite-Calcite
- 🟩 Illite-Chlorite
- 🟫 Illite-Kaolinite
- 🟪 Kaolinite-Alunite
- 🟦 NH4 Illite

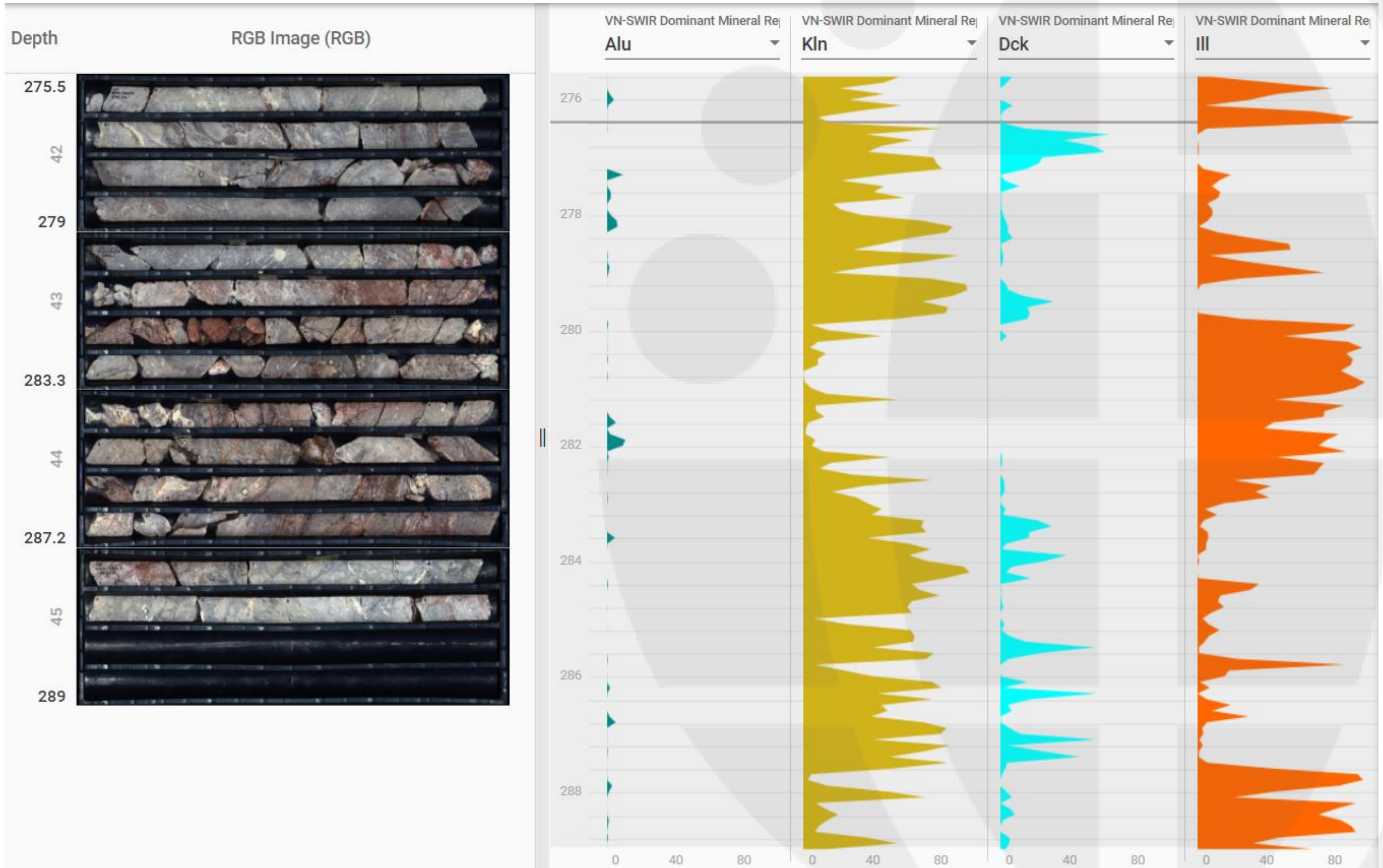


- The image reflecting the wavelength of the ~1475nm absorption in alunite has been included, along with a downhole plot of that feature extraction
- This feature is sensitive to K-Na substitution in alunite, and shifts to longer wavelengths when Na is added
- Na-alunite is often (as here) an indicator of temperature, and reflects hotter conditions. It would therefore be expected to form within or adjacent to fluid conduits (likely structures)
- So by mapping out these areas, as shown in the W1475 image and by the arrows on the downhole plot, the positions of structures can be identified
- With sufficient data, these can be predicted at depth and the boiling zone on the structures can be targeted by drilling



- Low temperature K-feldspar (adularia) is a common component of low sulphidation systems
- The mineral most often occurs within or adjacent to mineralized veins, however in some instances can be a pervasive alteration phase
- Being anhydrous, we are reliant on the LWIR to see this mineral. In some cases, particularly Mexico and the basin and range province of the western US, “adularia” is frequently the ammonium feldspar buddingtonite which is detectable in the SWIR
- The example on the left shows pervasive adularia (here, as most often the orthoclase structure) below a steam-heated kaolinite zone
- Note the amount of gypsum, which represents rapid weathering of disseminated pyrite in a tropical environment

Adularia



- The section on the left is through a high-grade low sulphidation vein
- Acid alteration minerals such as alunite, dickite and kaolinite are to be expected in the steam-heated zone above veining; however, in this case they occur within the vein itself
- Illite, as is expected, is a strong alteration phase
- The reason for this alteration signature is unclear from the spectral data alone, but could either represent telescoping in a tectonically active environment or the direct contribution of magmatic fluid

Atypical Alteration

- Intermediate sulphidation Au-Ag deposits are also a significant source of production for precious metals. They can be extremely high grade, are generally metallurgically simple (and as gold is often coarse are amenable to gravity recovery), are generally sizeable, and so are a preferred exploration target

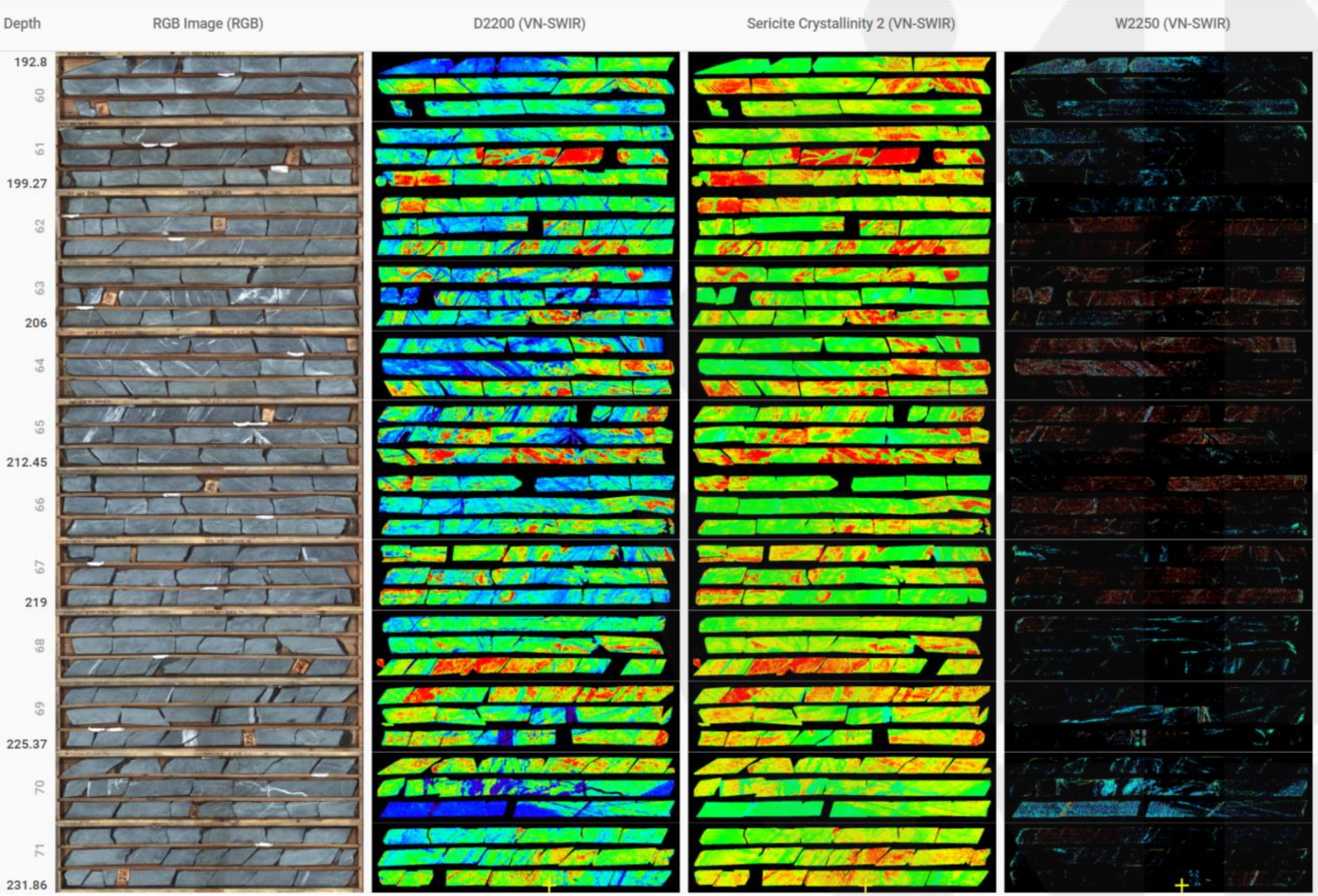
- Intermediate sulphidation deposits have a significant magmatic fluid component along with meteoric fluid which results in moderately saline and variably oxidized hydrothermal fluids that have good precious metal transport characteristics, and importantly are able to effectively transport base metals (especially Pb and Zn) leading to a diverse sulphide suite. These deposits are generally associated with active volcanic arcs with generally calc-alkaline volcanism, although back-arc extensional deposits (E-type) are known. These can form at quite high temperatures of up to 300°C

- Fluid:rock interaction and fluid mixing are important mechanisms for ore deposition. Mineralization occurs associated with moderately to steep dipping quartz veins and breccias, and broad lodes within which fine veining and stockworks occur. Alteration is dominated by muscovite and/or illite, zoning outwards to illite-smectite and distal propylitic

- A feature of intermediate sulphidation deposits is the presence of carbonate minerals as alteration phases within and adjacent to mineralization. These often have elevated Mn-contents due to high concentrations of that element in the hydrothermal fluid

Intermediate Sulphidation Introduction

Alteration Mapping



- The images on the left show the strength of white mica alteration (D2200), white mica crystallinity, and chlorite composition (W2250)
- This section shows an altered and mineralized zone with numerous thin quartz and calcite veins, within pervasive white mica (in this case muscovitic) alteration
- Note the correspondence between strong mica alteration and increased crystallinity, suggesting that these reflect zones of fluid flux (higher temperatures)
- Veining is just outboard of these flow zones, where fluid:rock interaction is optimal for quartz precipitation and mineralization
- Also note that although chlorite content is extremely low, the composition changes in the mineralized zone (W2250). This reflects chlorite precipitating as part of the sulphidation reaction

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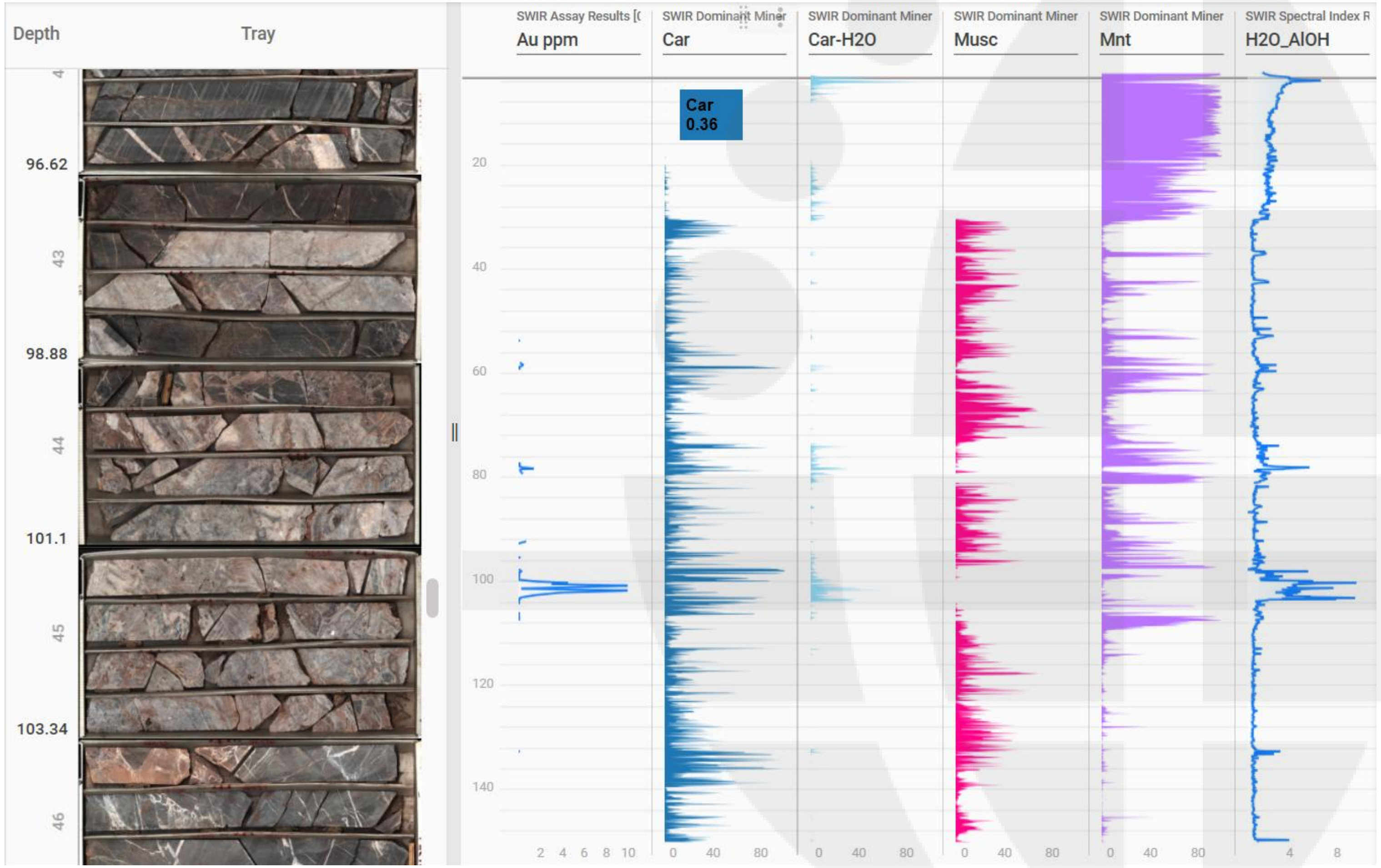
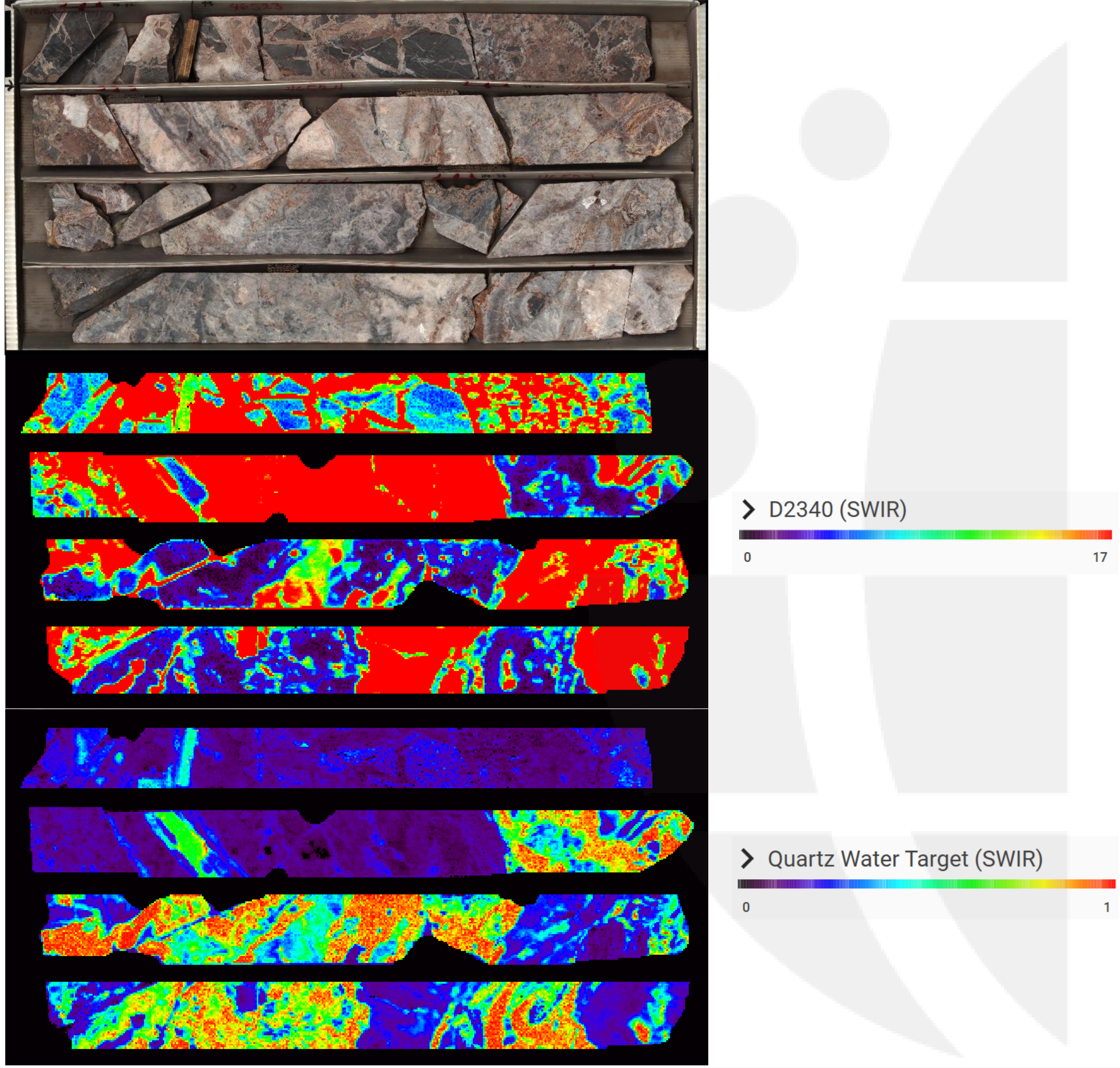
Alteration - Carbonate



- The images on the left show mineral mapping through an intermediate sulphidation vein
- Montmorillonite defines the supergene zone, though late overprinting clay is evident in deeper zones as well
- The vein shows the often very strong carbonate signature of these systems, carbonate occurs throughout the hole but is strongest around the mineralized vein in the form of fine calcite veins and occurs with quartz (note the elevated H2O_AlOH due to quartz) in the mineralised vein
- Muscovite forms a broad halo around the vein, extending 60+ metres in these permeable volcanics
- Two very narrow mineralised veins are evident slightly higher up the hole, which repeat the pattern seen in the main vein

Vein Detail



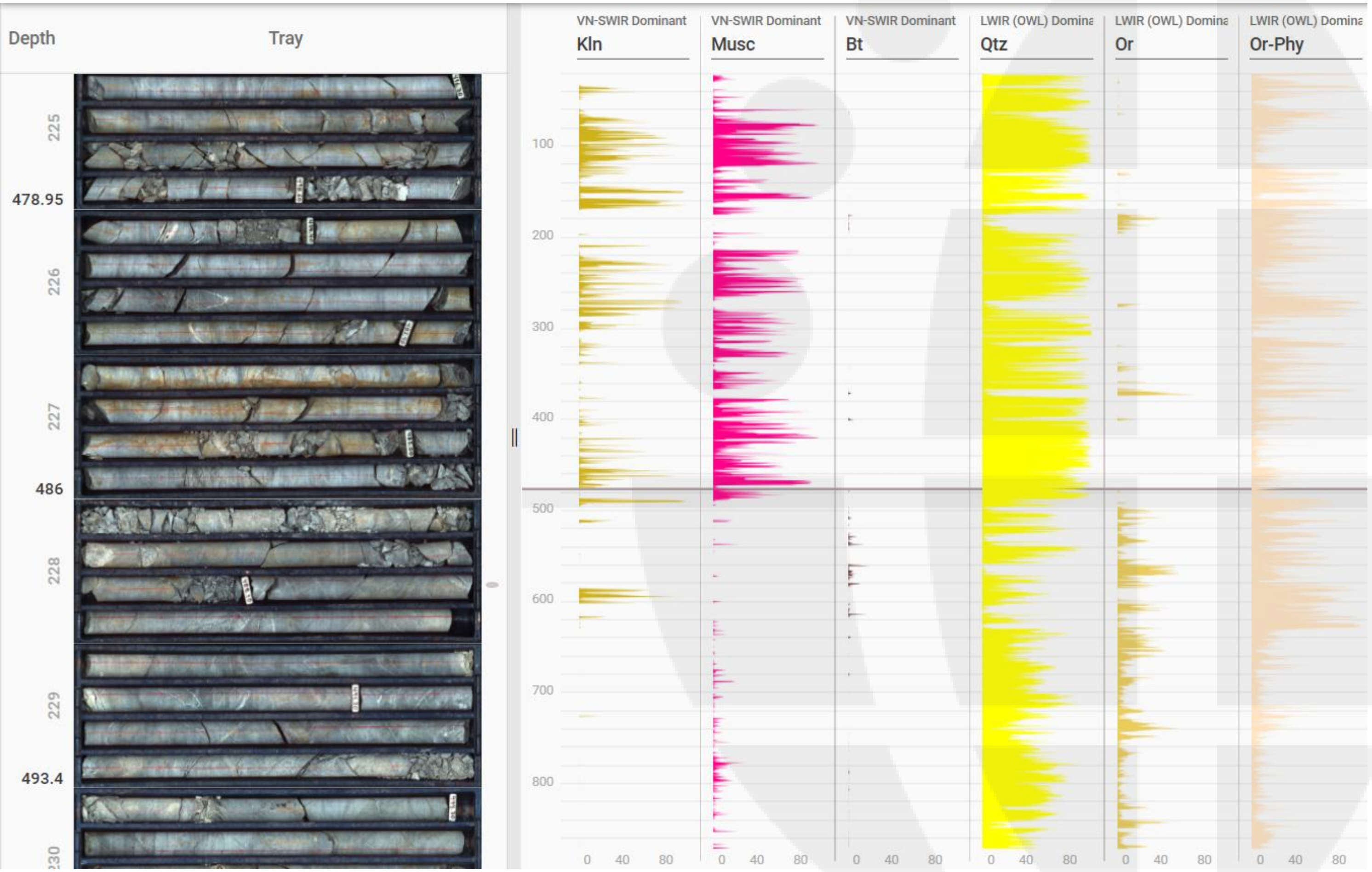
- The images on the left show detail of an intermediate sulphidation vein
- The strength of carbonate mapping is shown by the D2340 image in the centre, which records the depth of the ~2338nm calcite absorption. Red is where carbonate is strongly developed
- An algorithm was designed to track unbound water associated with quartz (principally fluid inclusions in vein quartz) and is shown at the bottom. The strongest quartz signatures are in warm colours
- Note the complex arrangement of quartz and calcite, which appear to show multiple overprinting, with some brecciation
- Evidence for multiple fluid pulses as in this example are a good indication of prospectivity, this particular vein averages about 10g/t Au

- High sulphidation Au-Ag (+Cu) deposits include some of the largest epithermal precious metals deposits known. They tend to be moderate grade, and can be metallurgically challenging, but the scale of deposit makes them a desirable exploration target
- High sulphidation deposits are the result of late-stage magmatic fluids, with a minor component of meteoric fluid. This produces a moderately to highly saline and generally oxidized hydrothermal fluid, with a high sulphur component that enhances metal transport. These deposits are invariably associated with active volcanic arcs with generally calc-alkaline volcanism, and are frequently directly associated with mineralised porphyries
- Dissociation of liquid and gas results in the characteristic large alteration systems. The gas phase preferentially carries sulphur, which forms sulphuric acid and leads to very low pH that favours alteration minerals such as silica, alunite, dickite, diaspore, zunyite etc., with mineralization generally being deposited from the fluid component that exploits open space created by the acidic gas phase
- Mineralisation occurs as breccias, stockworks and veins that vary between steeply dipping zones (that produce characteristic resistant “ribs”) and horizontal ledges. Identification and mapping of alteration is key for vectoring

High Sulphidation Introduction

Alteration Mapping

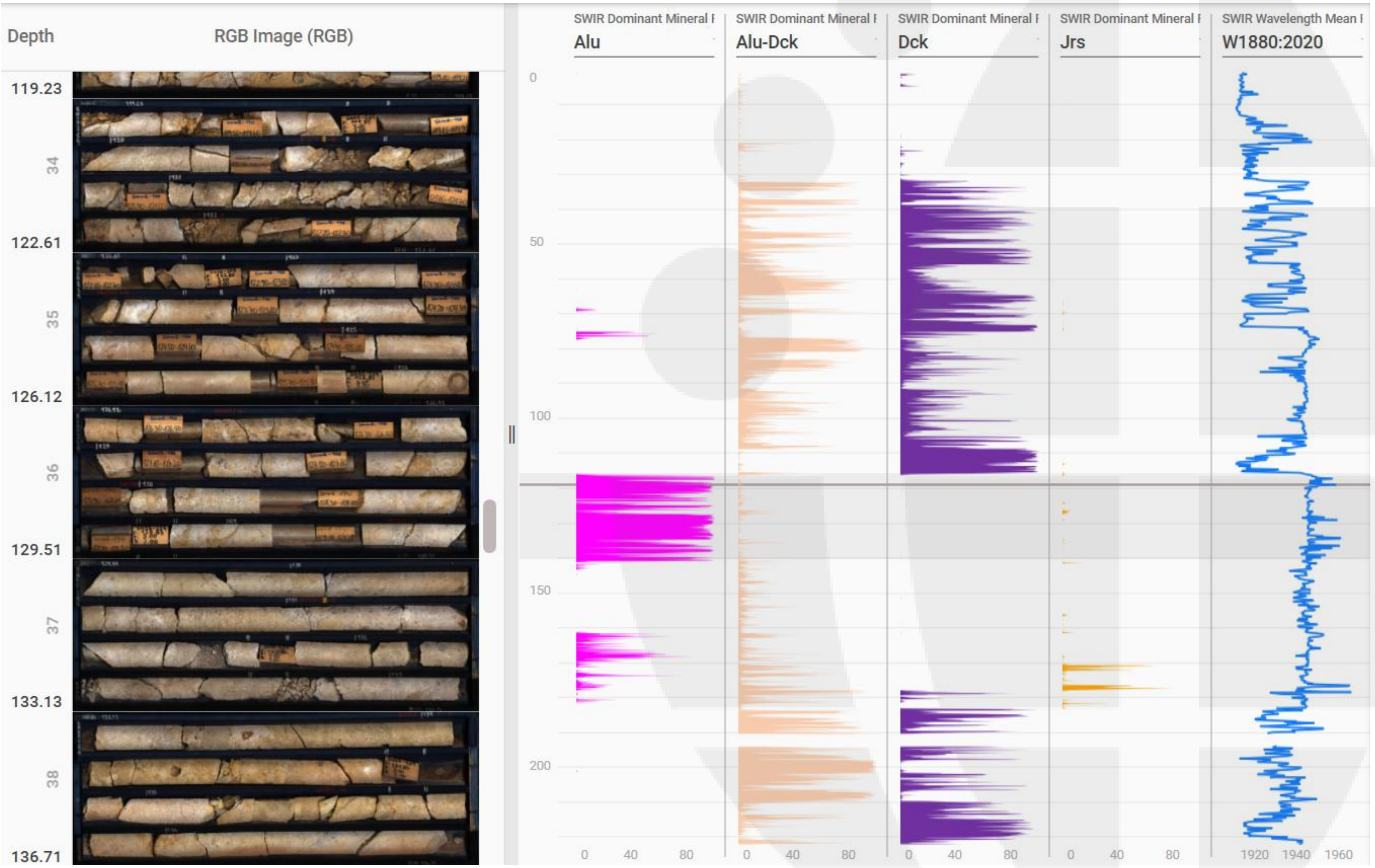
- The plots on the left show mineralogy through a high sulphidation intersection
- High sulphidation alteration is defined by alunite, dickite and kaolinite (minor zunyite and diaspore also present) with elevated quartz
- Note that the LWIR actually maps alunite more strongly than the SWIR, which is unusual and probably a reflection on the amount of quartz (vuggy silica) present
- The base of the hole has intersected relatively unaltered volcanics, in which feldspar is preserved with quartz. Note the colour change at ~180m that defines the lower contact of the strong high sulphidation alteration; however, the mineralogy shows that alunite and kaolinite persist for another ~60 metres within a partially altered zone



- The plots on the left show mineralogy through another hole from the same project as the previous slide
- High sulphidation alteration is weaker, and defined by kaolinite that is associated with muscovite and quartz to a depth of ~500 metres where an abrupt transition occurs
- Potassic porphyry alteration is represented by well developed and pervasive orthoclase (+ Al-phyllosilicate that based on the SWIR is kaolinite and/or muscovite) and biotite
- Biotite is only present below 500 metres, however orthoclase co-exists with kaolinite at shallower depths which on close inspection can be seen to overprint the K-feldspar
- This is a good example of a telescoped system with high sulphidation alteration being superimposed on a coeval porphyry

Porphyry Transition and Telescoping

Alteration Zonation



- The plots on the left show SWIR responses for a drillhole through a high sulphidation alteration system
- The zonation pattern revealed by mineral mapping reflects a core of very low pH alteration defined by alunite
- Jarosite occurs with alunite, and likely reflects oxidation of sulphides
- This grades outwards to an alunite-dickite and dickite dominated zone, reflecting slightly less acidic conditions caused by pH buffering by fluid:rock interaction
- Also included is a plot of the position of the water absorption feature (W1880:2020). Note how this is constant through the core of the alteration system, and at a long wavelength (~1955nm) reflecting unbound water in silica accompanying alunite

Conclusions

- Hyperspectral core imaging provides excellent data for epithermal exploration, across the entire spectrum of types
- Mineralogy and mineral chemistry provide information that defines alteration zonation, vectors towards higher temperature/low pH parts of systems that are more probable to host mineralization
- Crucially, spectral mineralogy can define alteration types that define the type of system at early exploration stages and so help determine likely geometries of mineralization (steeply dipping veins vs ledges, for example)
- While the SWIR can provide excellent mineralogical information, the LWIR for quartz and feldspars is a valuable addition