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Hyperspectral Core Imaging for Oil and Gas

Introduction

- Reservoir analysis is the key requirement for evaluating the producing potential of an oilfield, whether conventional, unconventional or oil sands
- Core is an extremely valuable asset for analysis, and subjected to a wide variety of tests to assess porosity, permeability, organic content, fluid saturation (and fluid type), mineralogy and thermal maturity among other measures
- Many of the geophysical tools applied provide a continuous downhole measure, however mineralogical tools such as XRD, SEM and thin-section analysis are undertaken on discrete plug samples
- Hyperspectral core imaging provides an inexpensive means of supporting and supplementing current analytical tools, by providing a continuous mineralogical record
- While spectral mineralogy is not quantitative, it can be calibrated using other mineralogical tools to provide continuous quantified mineralogy downhole
- This presentation outlines several applications for hyperspectral data, for more detail the reader is referred to:

  Linton P, Kosanke T, Greene J and Porter B (2023) – The application of hyperspectral core imaging for oil and gas. In Neal A, Ashton M, Williams LS, Dee SJ, Dodd TJH and Marshall JD (eds) – The role of core in twenty-first century reservoir characterization. Geol. Soc. London, pp 95-120

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- Hyperspectral core imaging is of particular value given:
  - It captures mineralogy in situ and so textural relationships can be easily seen and mapped
  - Since every pixel is imaged, quantitative counts of minerals can be extracted (spectral modal mineralogy). The addition of the long-wave infrared adds anhydrous silicates and sulphates, plus additional information related to carbonates
  - By extracting information related to absorptions (SWIR) or peaks (LWIR) the relative strength of spectral response provides a proxy for mineral abundance
  - By extracting absorption or peak positions, and shifts in those positions, the chemistry and texture of minerals can be examined and mapped
  - By compositing the data, truly representative downhole plots can be output at any desired resolution
  - TerraCore has provided data for all types of O&G reservoirs, including various types of conventional reservoirs, heavy oil sands and unconventional shale reservoirs

Hyperspectral Core Imaging

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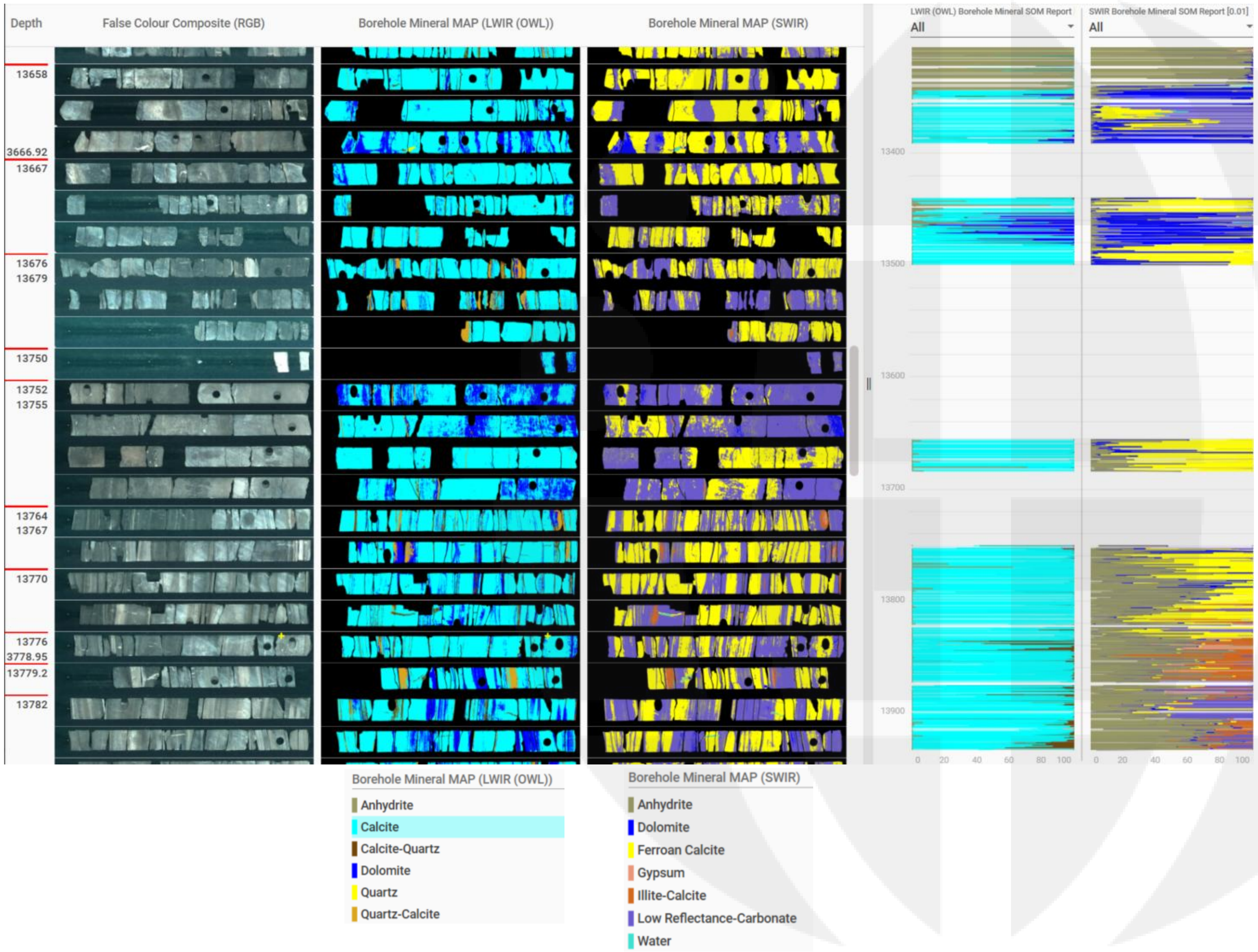


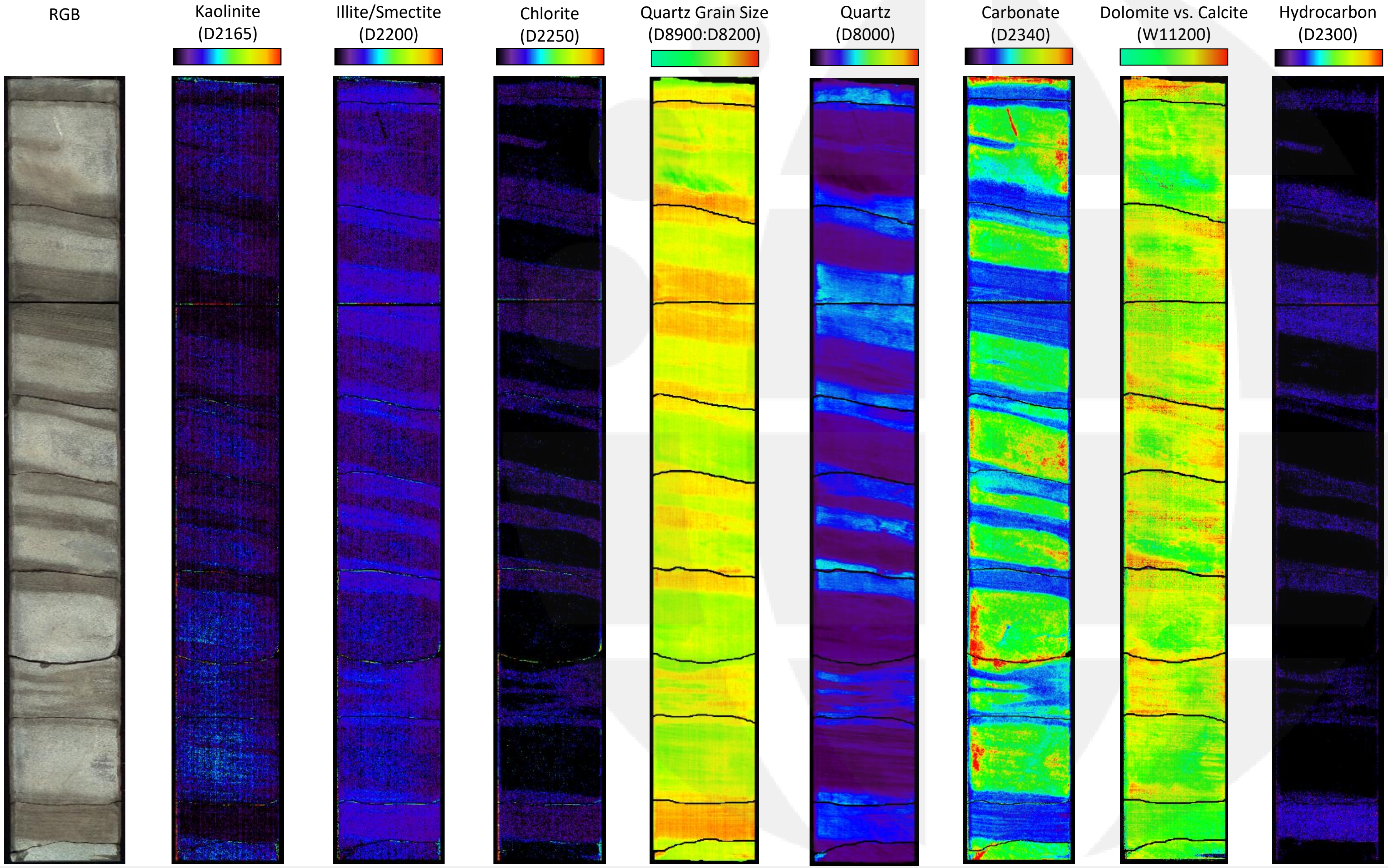
- Mineral maps are a basic product derived from the hyperspectral data. These can be viewed as both an image (to look at textural relationships) and as a downhole plot as shown on the left

- Pixels are classified according to their spectral signatures, and where appropriate mixed responses are recorded. At the high spatial resolution of the data these are most likely true mineral assemblages

- Due to the different responses in the SWIR and LWIR, these ranges are mapped and presented separately as shown for this core from the Austin Chalk. The Austin is one of the few cases where the SWIR has strong mineral responses

- Mineral maps are a yes/no decision product, and so may fail to highlight subtle and gradational mineralogical relationships

Mineral Mapping



- In addition to mineral mapping, we can also examine spectral features to gain additional information related to qualitative mineral abundance, composition, and texture
- The plots on the left are for a section of Middle Bakken core
- These plots can identify and highlight subtle and gradational relationships that can be missed by mineral mapping
- Downhole composites can also be viewed

Spectral Features

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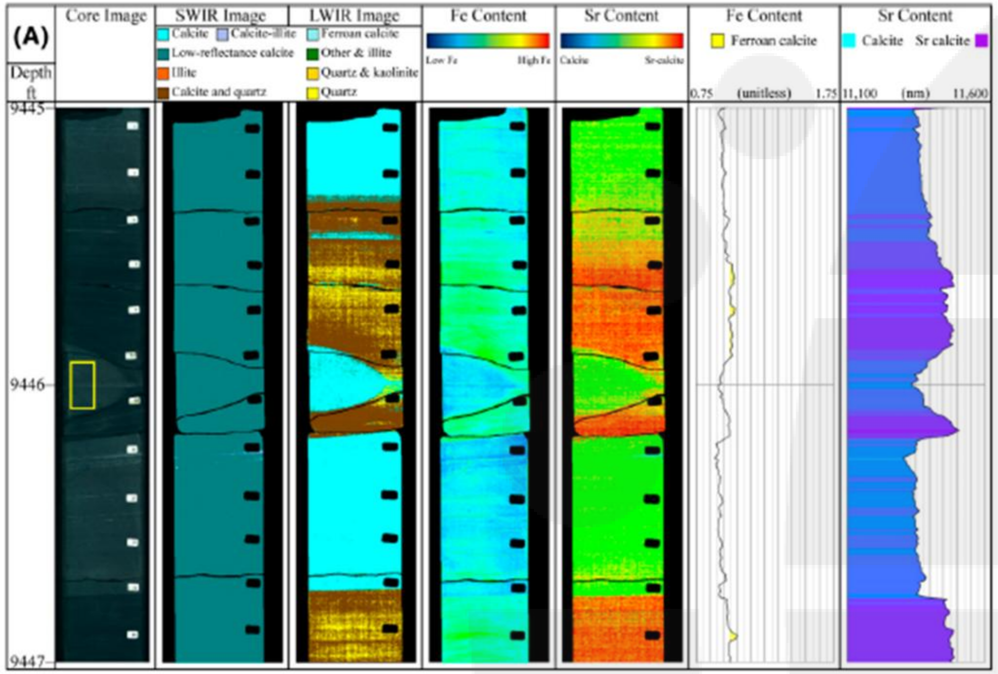
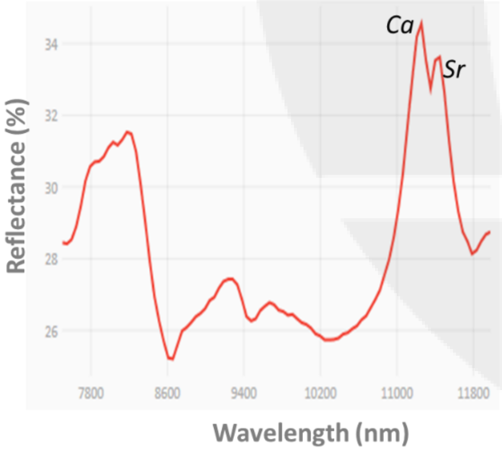
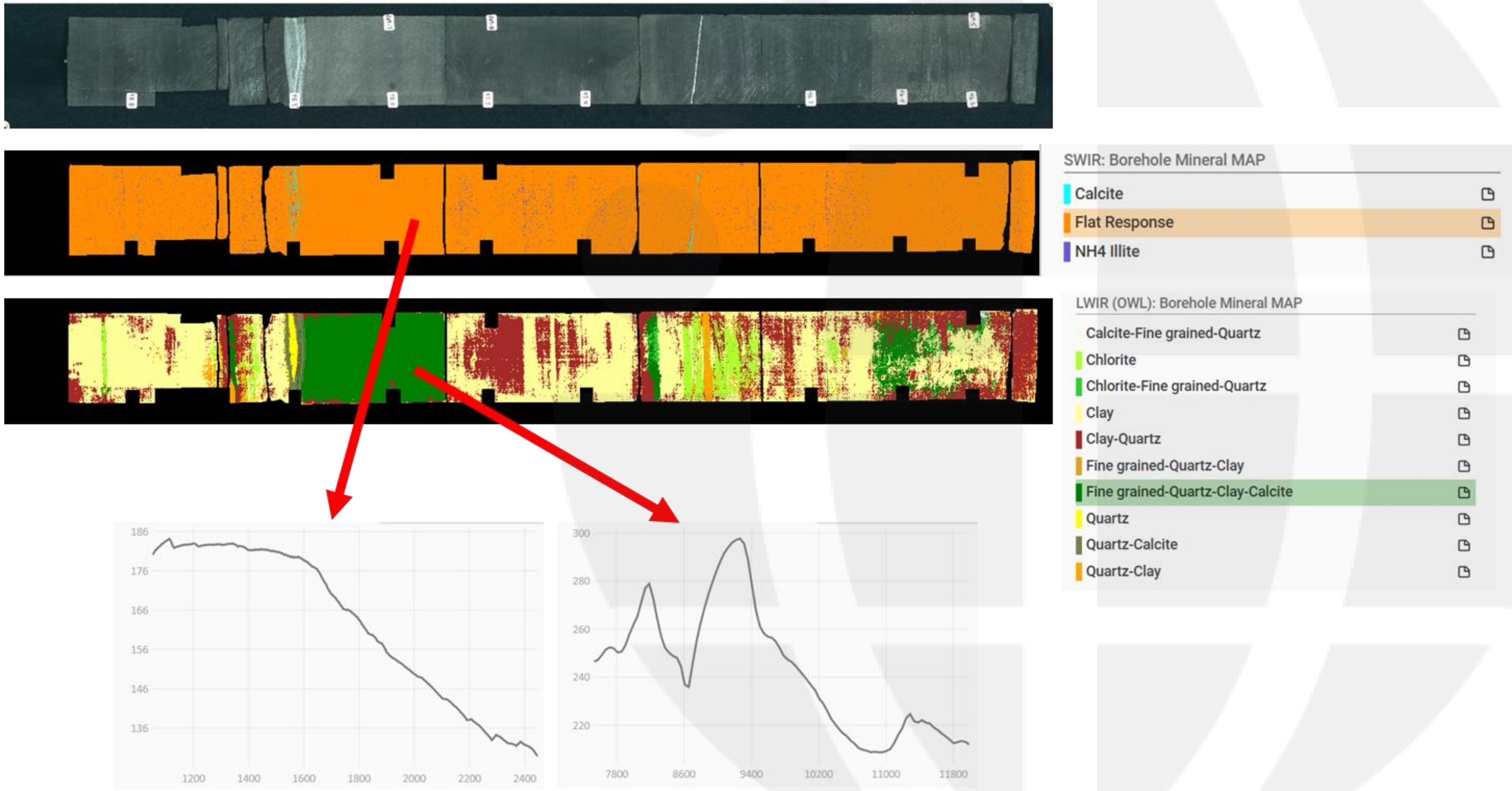




- The images on the left show a sequence through a coccolith-rich limestone unit in the Eagleford Formation
- A double carbonate peak was noted in the hyperspectral data as shown bottom left, with a typical calcite peak at 11250nm and an additional peak at 11420nm
- XRF analysis shows that the longer wavelength peak is caused by substitution of strontium into calcite
- The normal calcite peak is related to the limestone unit, while the Sr-rich calcite is preferentially formed within the coccolith fossils. The small spot size of the hyperspectral data is able to resolve the two spectral types

Mineral Chemistry – Carbonates

The Critical Role of the LWIR



- On the left are shown mineral maps derived from the SWIR and LWIR for a section of core from an unconventional reservoir
- The SWIR uses reflected light to record information, and in cases like this (which are common in oil and gas cores) the rocks are so dark that little return of energy is recorded by the spectrometer. Besides minor calcite, a flat aspectral response is recorded for ~99% of the pixels
- The LWIR, by contrast, measures reflected heat energy and so is less affected by dark rocks. This allows for mineralogical mapping in these dark lithologies, and makes the addition of a LWIR camera essential for oil and gas applications

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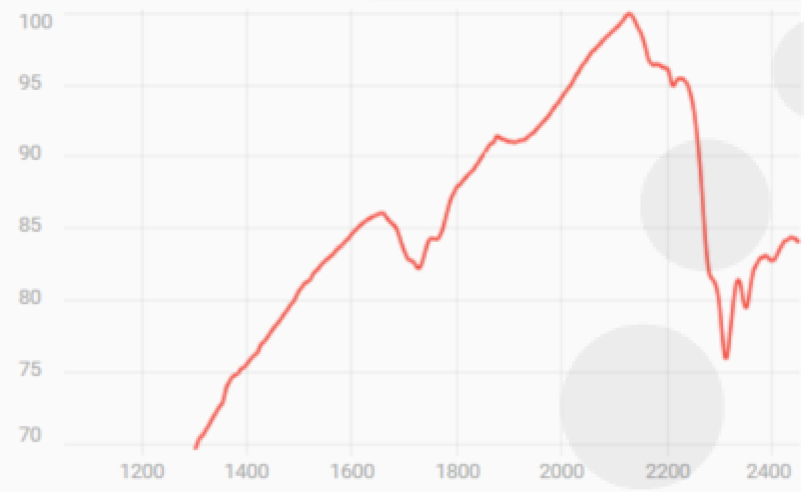

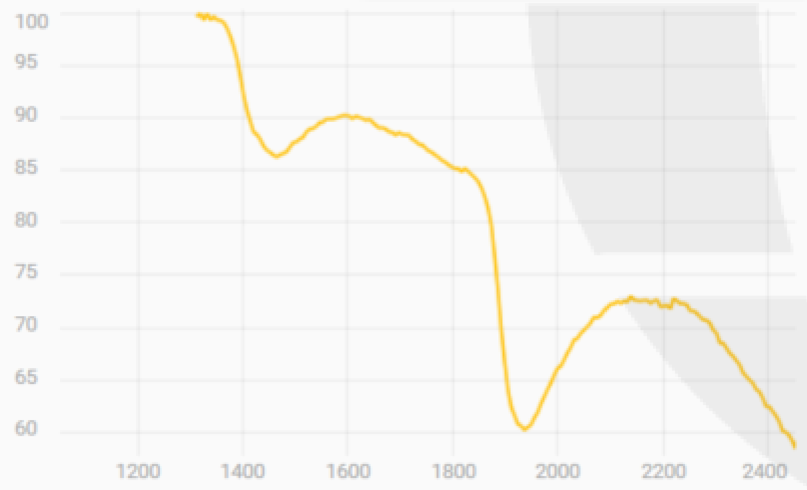

- Hydrocarbons, both liquid and gas, are responsive in the SWIR. The top spectrum on the left shows a typical hydrocarbon signature, with a distinctive positive slope between 100 and 2000nm plus a number of sharp absorption features at ~1700-1730 and 2310nm
- Water is shown on the lower left. It only displays two large and broad features that correspond to the position of the O-H and H-O-H bonds respectively, and also lacks the characteristic upward slope of hydrocarbon, Care needs to be taken to ensure that the water signature is not related to unbound water in quartz, for which the LWIR can be used for confirmation
- We have frequently encountered mixed hydrocarbon-water signatures
- Hydrocarbons can be speciated in the mid-wave infrared (MWIR), an exciting new research direction as practical instrumentation becomes available for incorporation on a core imaging workstation
- Care should be taken when looking at historical cores, where liquid phases have often been lost during storage

Hyperspectral Responses of Liquid Phases

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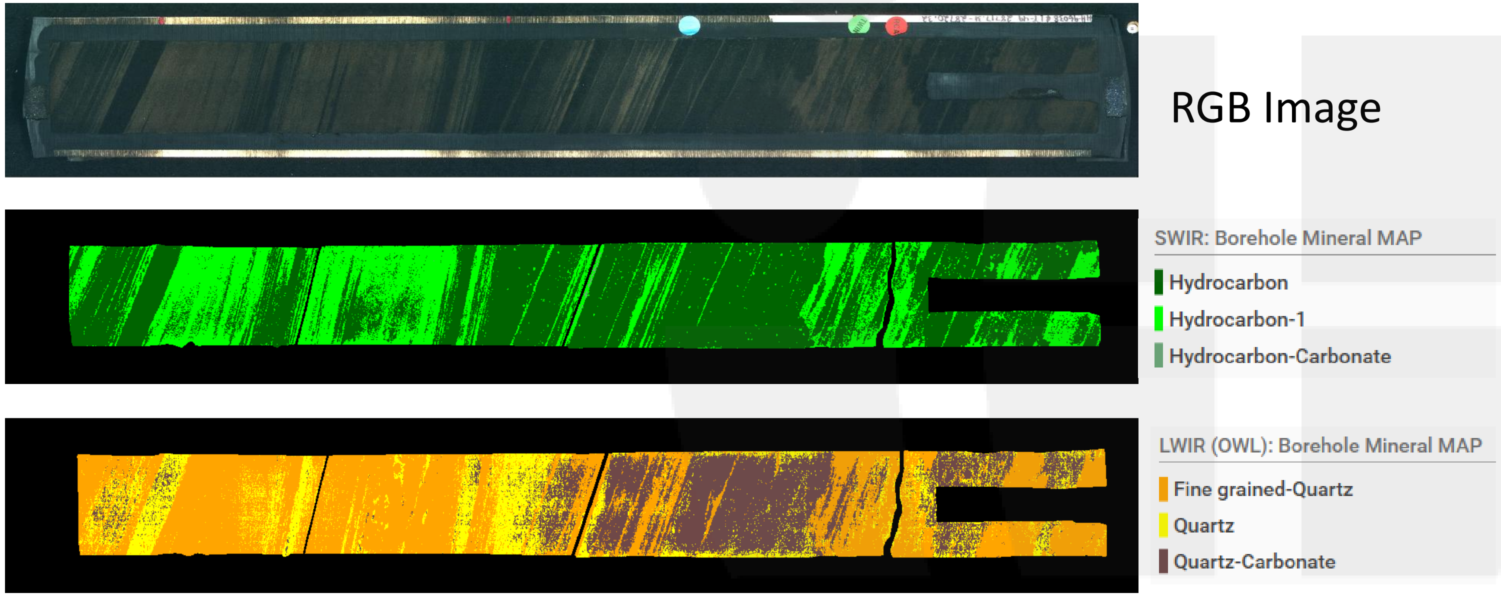
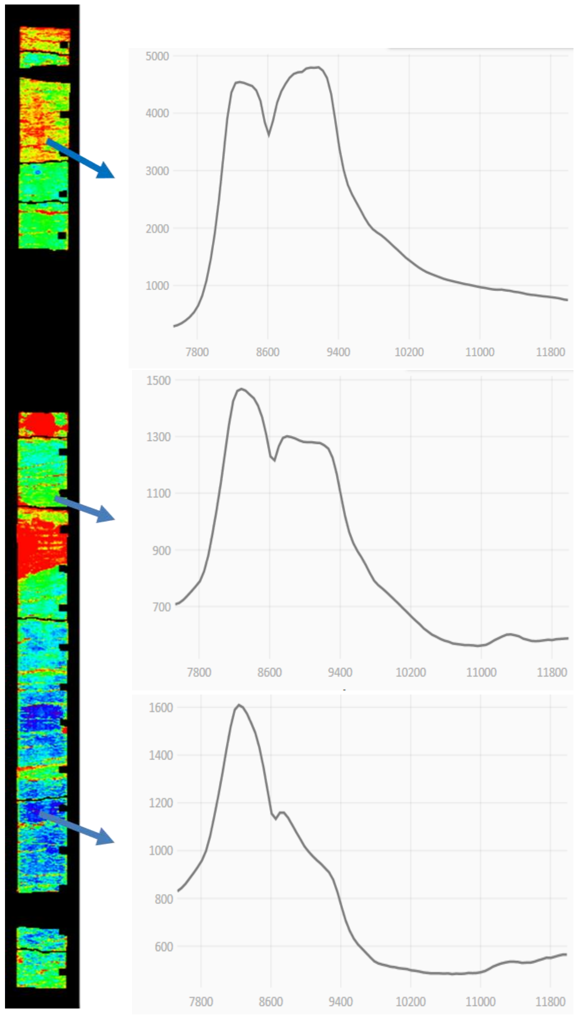
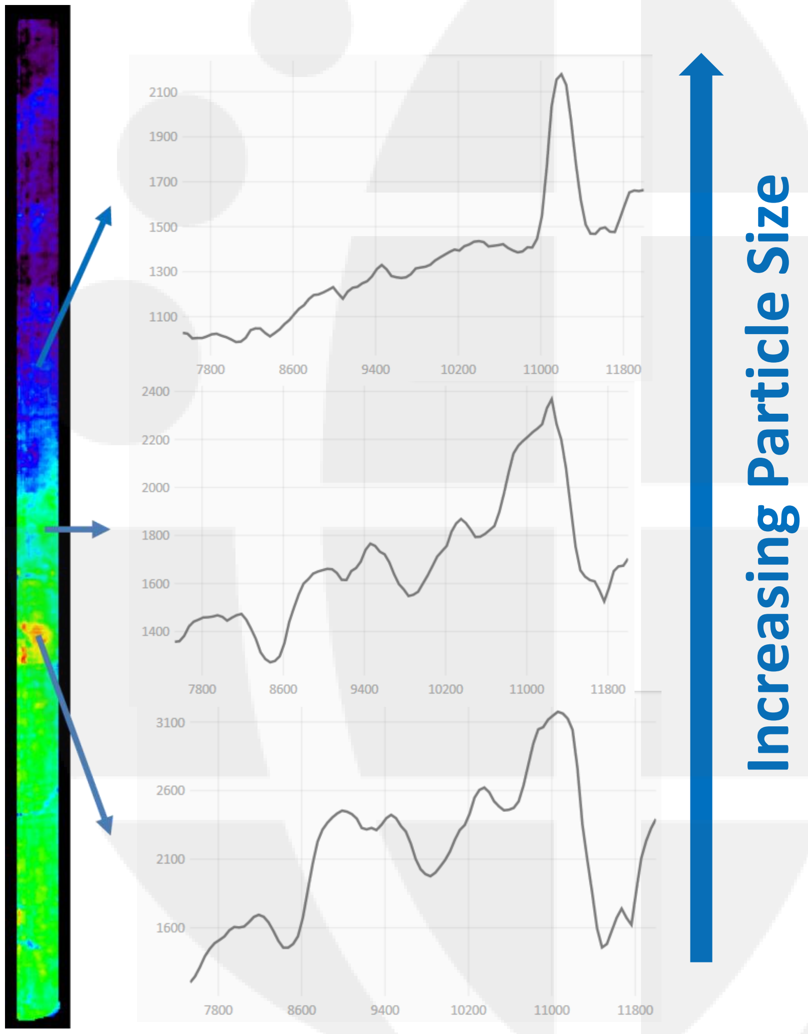
Seeing “Through” Liquid Phases



- In oil saturated sediments, mineralogical information is lost in the SWIR due to the strong response of hydrocarbons
- However, liquids do not respond strongly in the LWIR and so are in a sense transparent
- This allows, as in the oil sands example shown on the left, for mineral phases to be identified and mapped in saturated horizons
- This again highlights the importance of collecting LWIR data





- For most minerals, LWIR signatures vary according to particle size. The most useful and predictable variations are observed in quartz and carbonate
- Shown on the far left are quartz variations, alongside calcite variations. The shape and magnitude of spectral peaks changes as particle size increases or decreases
- This is especially useful for assessing potential cement of either mineral species, or where very fine-grained material might occur that inhibits fluid movement
- Fine calcite is also mapped in chalk horizons, allowing mineralogical separation from limestone

Mineral Texture – Porosity and Permeability

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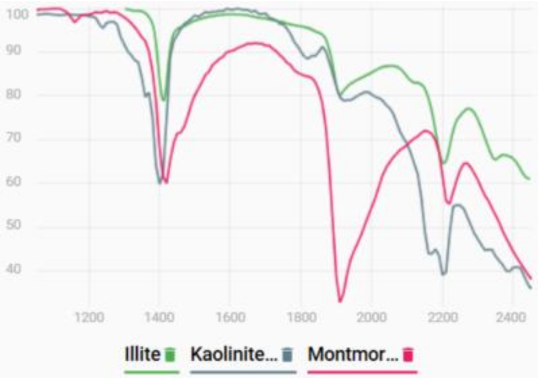

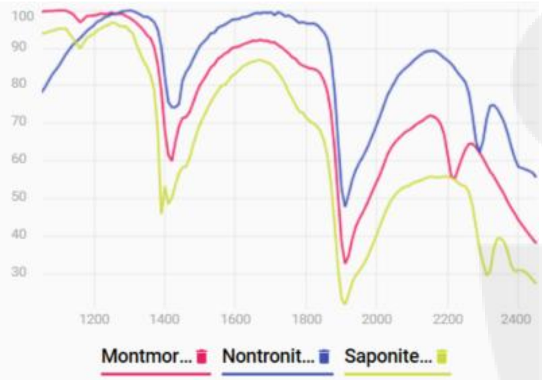

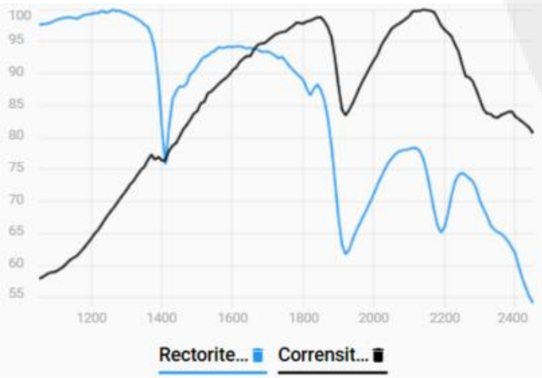

- Clay minerals can be directly identified and mapped using hyperspectral imaging, with separation of illite, kaolinite, chlorite and smectite possible. The plot at the top left shows reference spectra for illite, kaolinite and montmorillonite to illustrate spectral differences
- Using the position of cation bond absorptions, smectite chemistry can be mapped ranging from Al-rich through Fe-rich to Mg-rich as is shown in the plot in the centre
- Spectral shapes also provide information related to clay crystallinity and interlayering. The plot at the bottom shows an interlayered illite-smectite and an interlayered chlorite-smectite, where the main differences are in the ~1910nm water absorption (which is diminished in interlayer clays due to the lower content of bound water in the clay structure), and in the case of interlayered chlorite-smectite in the addition of cation absorptions related to chlorite

Clay Types – Porosity and Permeability

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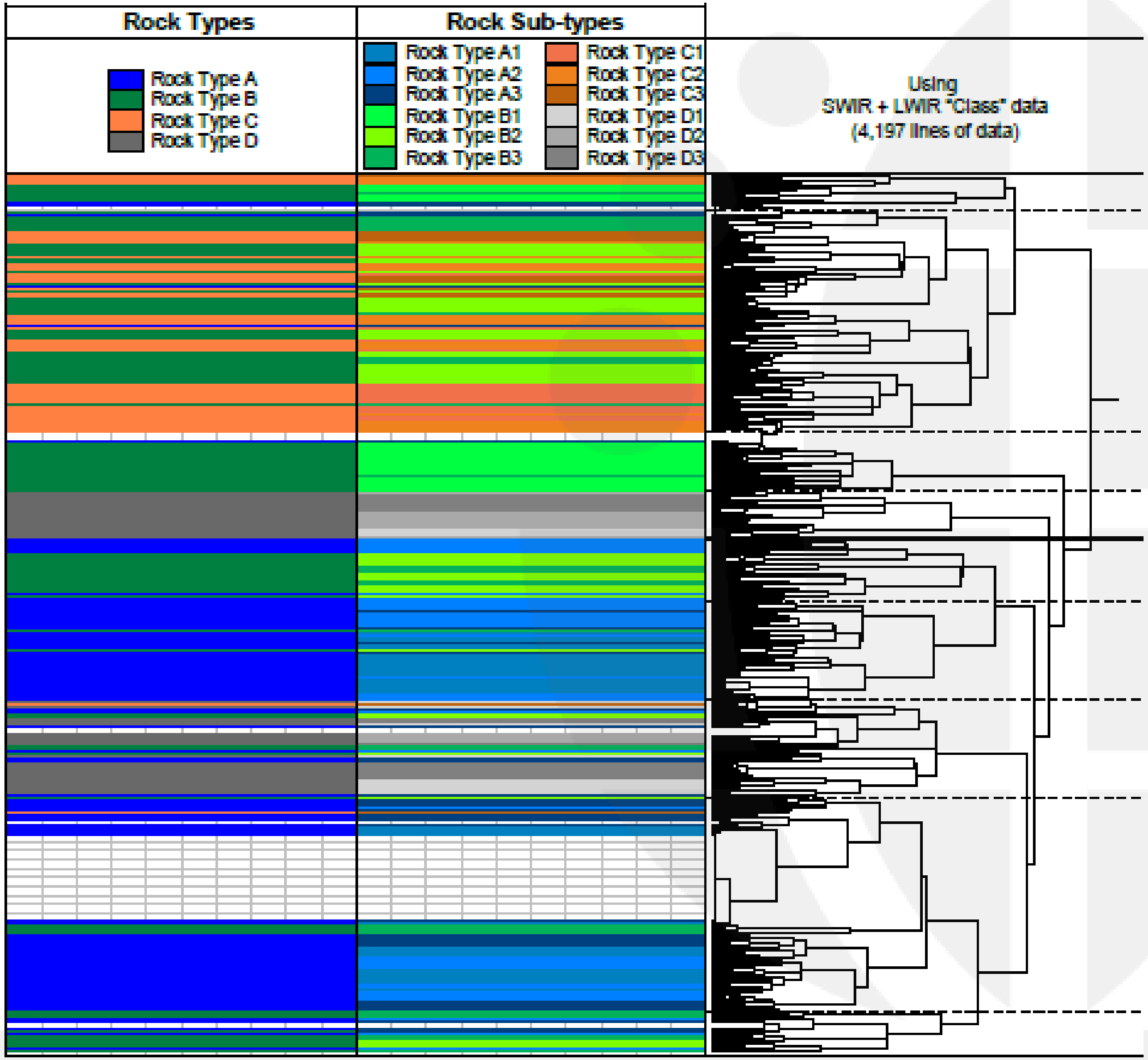

- As in input to mineral mapping, we use a self-organizing map (SOM) algorithm. This produces a set of classes, that can be mineralogically interpreted by a spectral geologist to construct the mineral map
- However, the uninterpreted SOM offers a great deal of unsupervised information that can be used for statistical analysis. The image on the left shows hierarchical cluster analysis applied to the SOM data from both SWIR and LWIR to generate a set of statistically similar classes that represent different rock types
- Armed with this product, XRD and SEM plugs can be better selected to ensure sampling representivity for those analyses

Rock Typing

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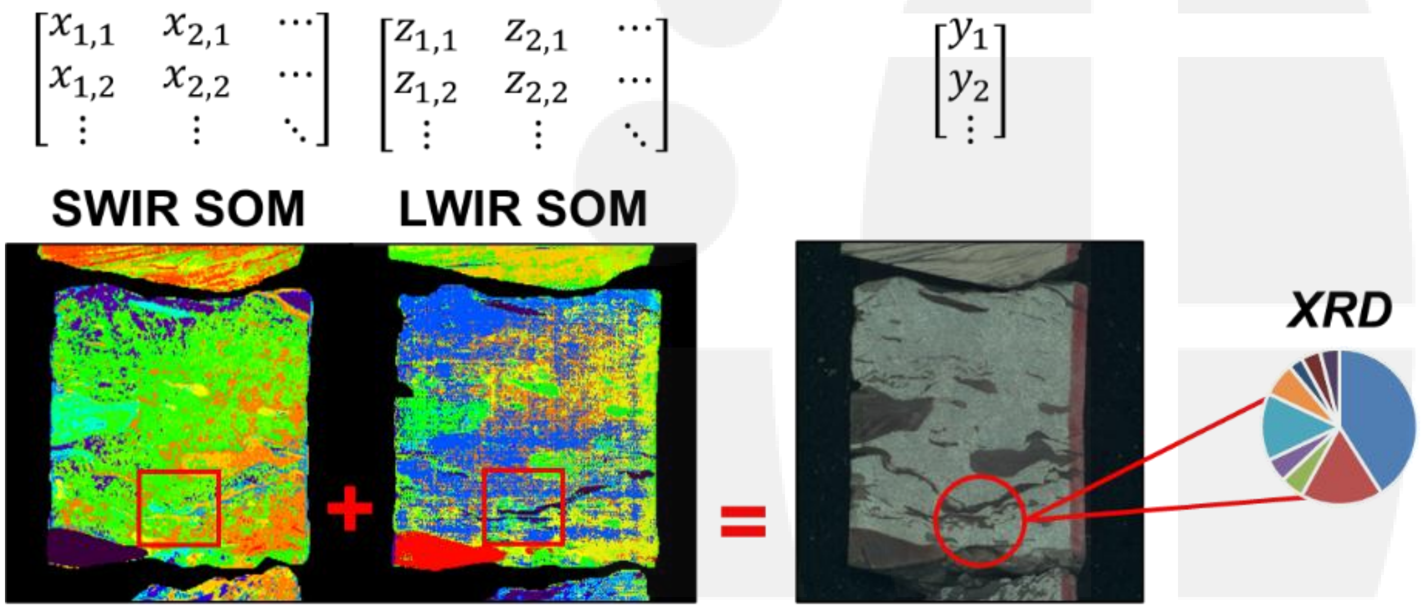

- As mentioned earlier, hyperspectral data are not directly quantitative due to the non-linear behaviour of spectral responses in mixtures and/or assemblages. While peak or absorption strength is related to mineral abundance, we can only be semi-quantitative
- We can again use the SOM data for both SWIR and LWIR to link to quantitative mineralogy, whether derived from qXRD or SEM. This is done by extracting the spectral data for each sampling point, and then using a multilinear regression to link SOM classes to quantified mineralogy as shown on the left
- Once regression statistics are obtained, they can be applied to the entire hyperspectral dataset to generate continuous and calibrated downhole mineralogy

Calibrated Mineralogy

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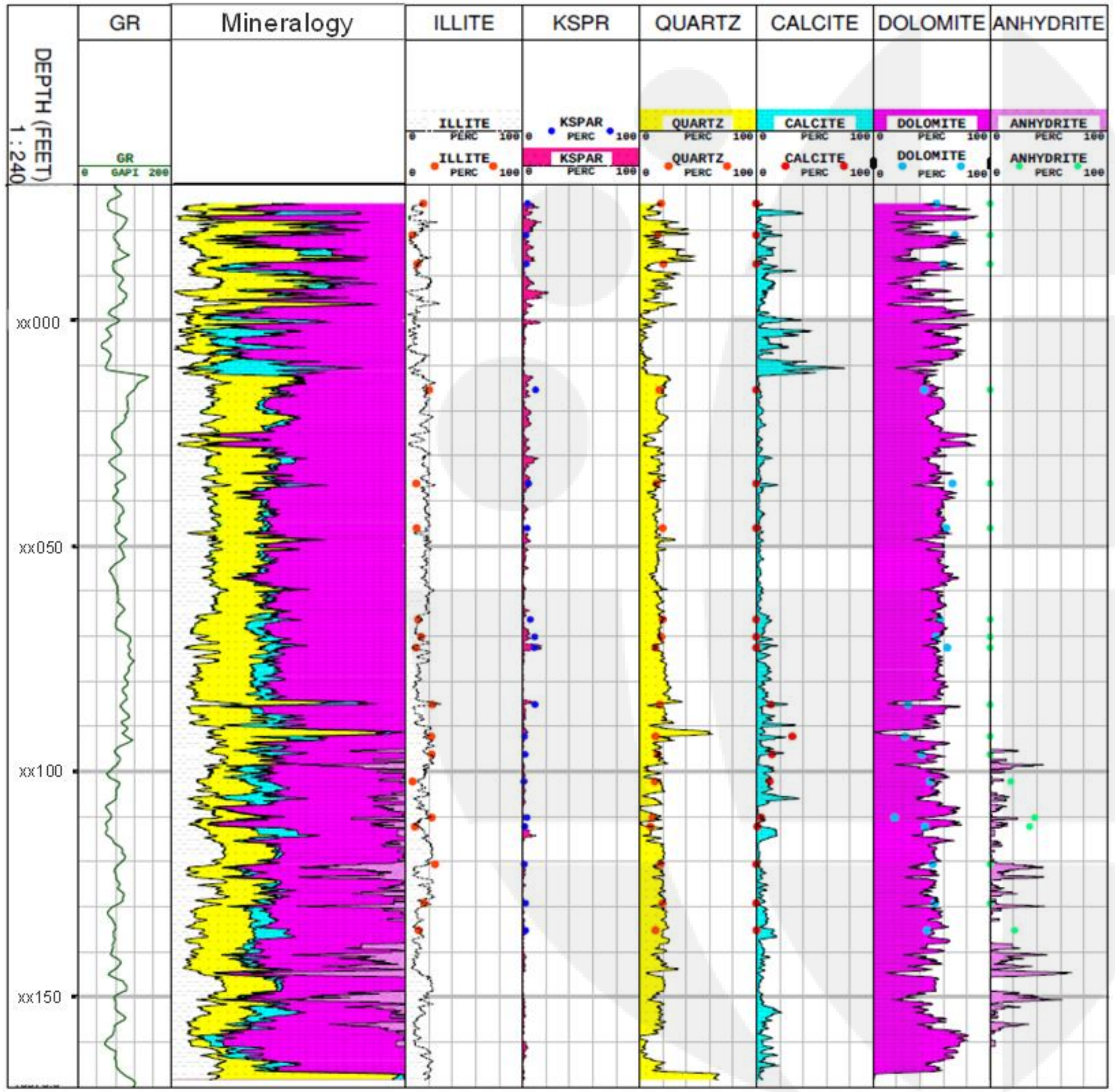

- The plot on the left shows calibrated mineralogy for an entire drill-hole, using combined SWIR and LWIR SOM information correlated to quantitative XRD
- The small coloured circles on each mineralogical plot show sample positions, and the actual mineralogy for each sample
- Overall agreement is very good, some discrepancies are noted that could either reflect very low mineral concentrations, or that available sampling is not quite sufficient to extract a perfect correlation (as appears to be the case towards the bottom of the hole)
- It should be noted that K-feldspar was not identified during mineral mapping due to its very low concentration, however it is able to be correlated. It is evident that despite low abundance Kspar has a measurable effect on spectral signature
- Note that this same concept can be applied to predicting TOC content

Calibrated Mineralogy

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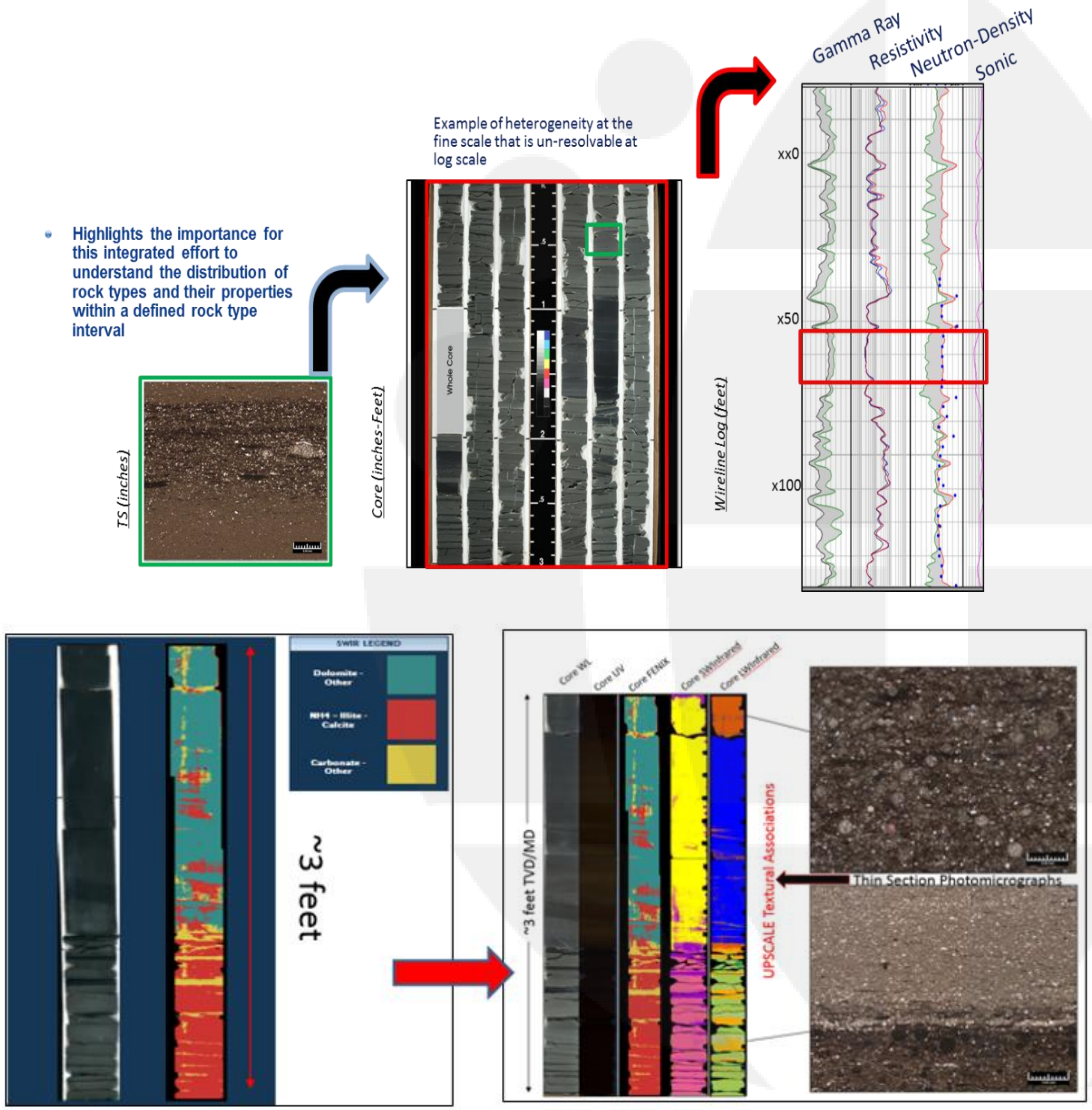

- Hyperspectral data are collected at very high resolution (<1mm pixel size), and continuously along the entire length of a core
- The combination of fine sampling and continuous measurements makes the data useful for linking to very fine-scale and discretely sampled data such as petrography, and then being able to effectively upscale that information to the log
- This allows for more effective application of data and interpretation of wells

Upscaling from thin-section to Log

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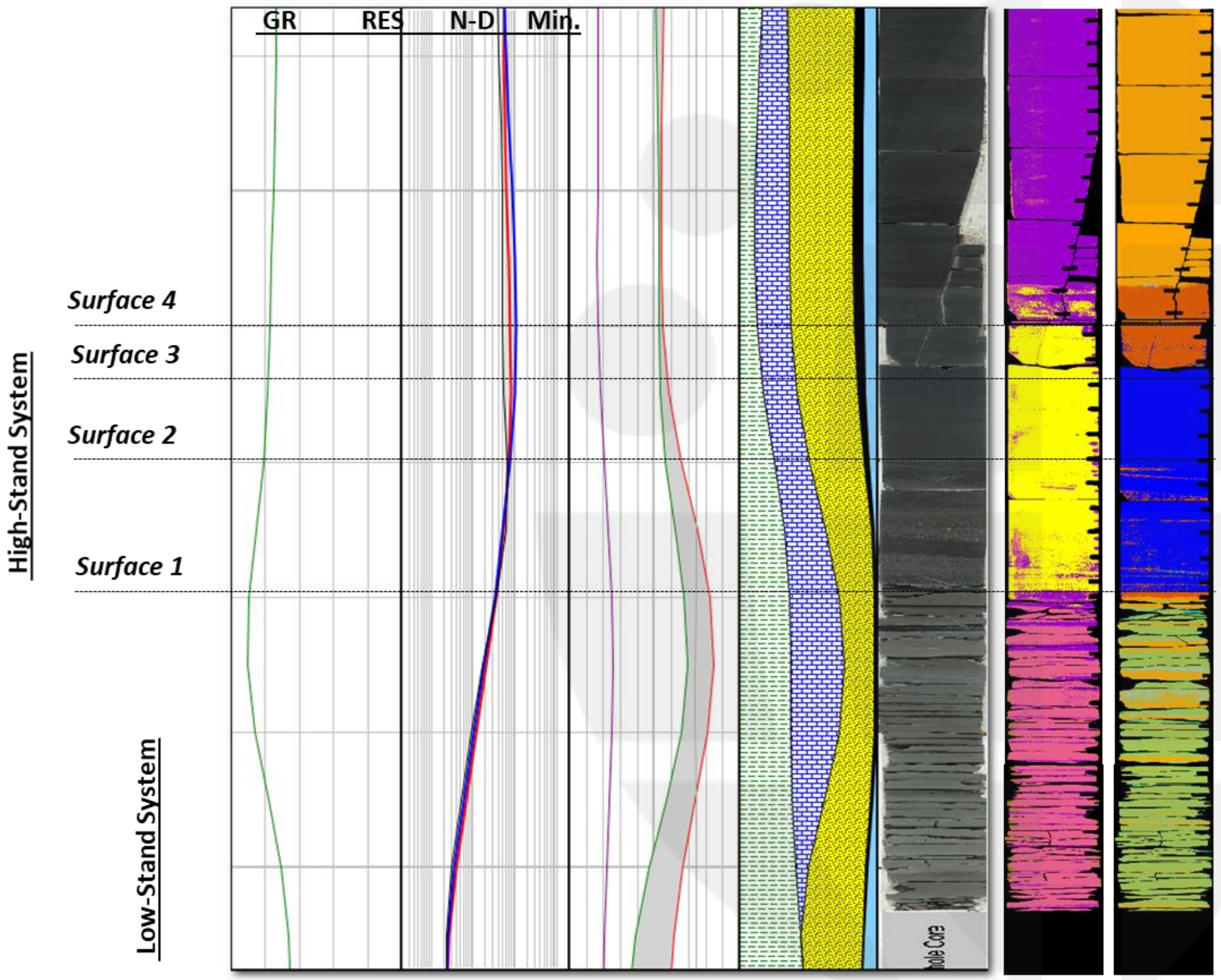
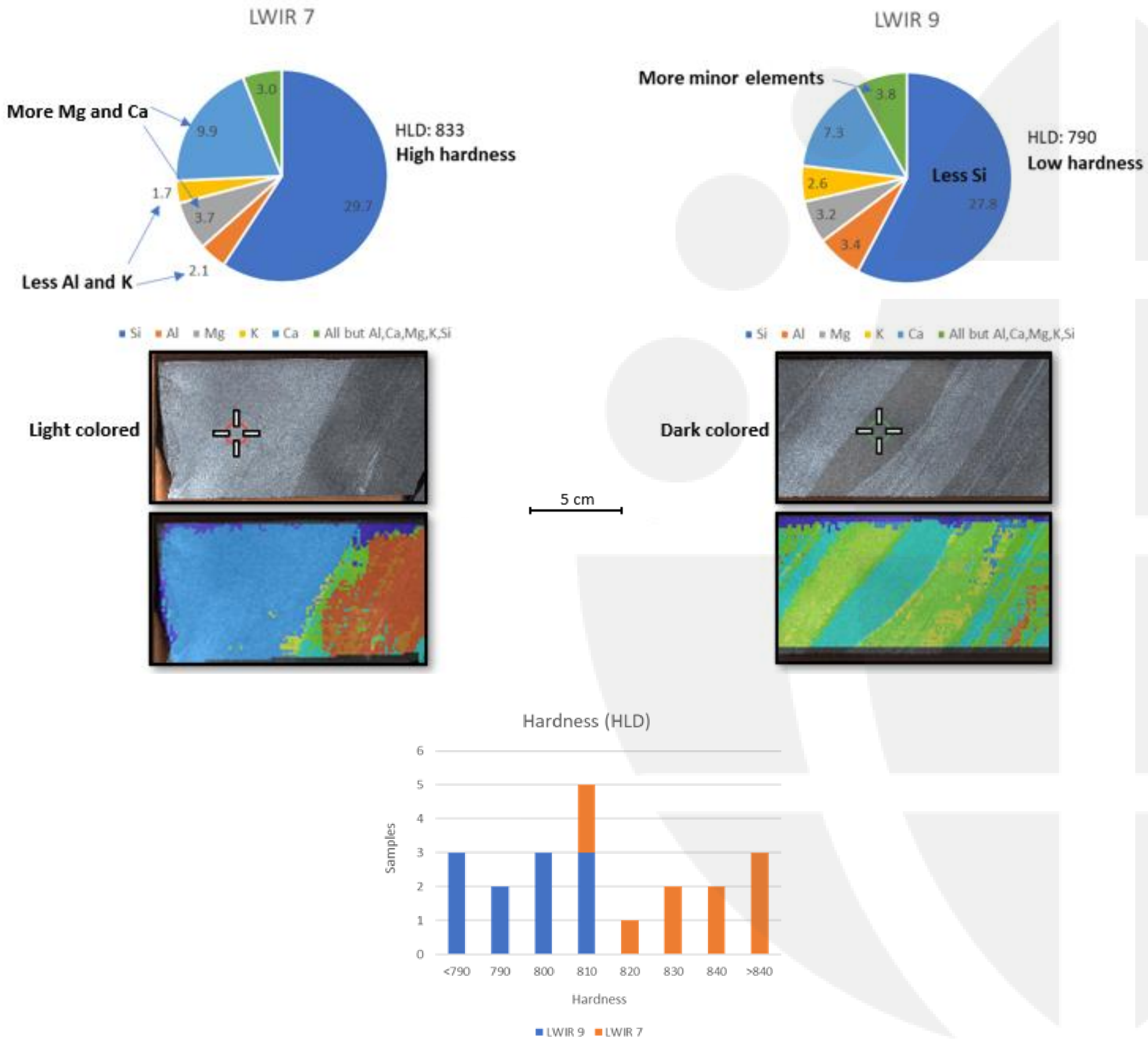


- We can combine hyperspectral imaging (which provides mineralogical and textural context) with core white light photography and open hole wireline log data to better identify sequence stratigraphic surfaces
- This provides an integrated data set to ‘up-scale’ from core description scale to wireline resolvable scale
- This aids in overall sedimentologic to petrophysical calibration, and depositional systems understanding

Upscaling – Sequence Stratigraphy



- Hyperspectral data have been used in the hard-rock environment to predict rock hardness during processing
- Using the same concept, the data can be used to produce continual measurements from discrete hardness samples collected using a Schmidt hammer or similar device
- The example on the left shows variation between two LWIR SOM classes that map individual silt beds
- While they vary only slightly in chemistry, they are mineralogically separable, and are quite distinct in terms of harness as shown by the histogram of hardness measurements
- The next step is to build a correlation, and from that a continuous hardness profile

Rock Strength

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Conclusions

- Hyperspectral core imaging provides excellent data for oil and gas applications
- Mineralogy, texture and mineral chemistry can all be mapped to aid in interpretation of reservoir materials and quality
- While not directly qualitative, the data can be linked to quantitative mineralogical techniques to provide a continuous mineralogical record of a well. This same approach can be used to predict TOC, and also rock strength
- The combination of high spatial resolution and continuous coverage makes the data ideal for linking to and upscaling detailed analyses such as petrography
- Early application and analysis of core imaging provides a means to ensure sampling representivity for other analytical techniques